DIELECTRIC PROPERTIES OF SOILS AS A FUNCTION OF MOISTURE CONTENT

REMOTE SENSING LABORATORY

RSL Technical Report 177-47

Josef Cihlar
Fawwaz T. Ulaby

November, 1974

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

In studying applications of microwave remote sensing techniques to agricultural, hydrological, and other related problems, the soil dielectric properties are of considerable importance. In recent years, numerous soil dielectric constant measurements have been made. Due to the complexity of the data acquisition procedure, however, the number of measurements in a single experiment is usually too small to permit a systematic analysis of the effects of the various parameters that influence soil dielectric properties.

The objective of this report is twofold: 1) to present soil dielectric constant measurements obtained by various researchers in one publication, thereby assisting in analysis and utilization of microwave remote sensing data and 2) based on these measurements, to determine the dependence of the dielectric constant on various soil parameters. Moisture content is given special attention because of its practical significance in remote sensing and because it represents the single most influential parameter as far as soil dielectric properties are concerned. From the experimental measurements collected in this report, relative complex dielectric constant curves are derived as a function of volumetric soil water content at three frequencies (1.3 GHz, 4.0 GHz, and 10.0 GHz) for each of three soil textures (sand, loam, and clay). These curves, presented in both tabular and graphical form, were chosen as representative of the reported experimental data. Calculations based on these curves showed that the power reflection coefficient and emissivity, unlike skin depth, vary only slightly as a function of frequency and soil texture.

1.0 INTRODUCTION

The target-sensor interaction process in remote sensing is governed by the target geometry and dielectric properties relative to the sensor parameters. At microwave frequencies, the dielectric properties of soils are particularly important because 1) they are very susceptible to moisture content, and 2) at incidence angles close to nadir, the target response of vegetation-covered surfaces can be influenced by contribution from the underlying soil. These characteristics have recently stimulated considerable research efforts to ascertain the operational feasibility of microwave sensors in remote soil water content determination (Appendix A).

The relationship between dielectric properties and soil characteristics has not been dealt with systematically, partly because experimental data are presented in a variety of sources. The purpose of this report is to analyze the behavior of soil dielectric properties at microwave frequencies as a function of several soil variables.

2.0 TARGET-SENSOR INTERACTION

The target response in the microwave region of the electromagnetic spectrum can be characterized in terms of its backscattering coefficient for active sensors (radar) and in terms of its emissivity for passive radiometers. Both quantities are functions of the following sensor and target parameters:

Sensor Parameters

1. Frequency
2. Incidence angle
3. Polarization

Target Parameters

4. Dielectric properties
5. Roughness of the surface and of subsurface from which a measurable radiation is reflected or emitted (relative to wavelength)
6. Thermometric temperature of the surface and subsurface material.

The effects of the first five parameters are explicit for either active or passive sensors. Thermometric temperature affects the surface scattering and emission character through its influence on the dielectric properties. Moreover, the radiation measured by a radiometer is directly proportional to the target thermometric temperature.

Dielectric properties of a medium influence the radar scattering coefficient and the radiometer emissivity in two ways: a) through the Fresnel reflection coefficient and b) by defining the effective depth in the medium responsible for the backscattered or the emitted energy. Hence, before discussing the dielectric properties of soils, it might be helpful to define these wave propagation parameters in mathematical form.

2.1 Reflection Coefficient

The Fresnel reflection coefficient r is defined for a perfectly smooth interface between two media. It relates the magnitude and phase of the reflected electric and magnetic fields to those of the incident fields of a plane wave. In terms of the subject of this report, the parameter of interest is the power reflection coefficient, $R = r^2$. If the incident wave is in air (assumed to have the same electromagnetic properties as vacuum) and the reflecting medium is homogeneous, then R is given by (Hidy, et al., 1972):

$$R_h = \frac{[(p-\mu)^2 + q^2]}{[(p+\mu)^2 + q^2]} \tag{1}$$

$$R_v = \frac{[(\mu k_1 - p)^2 + (\mu k_2 - q)^2]}{[(\mu k_1 + p)^2 + (\mu k_2 + q)^2]} \tag{2}$$

where h and v are subscripts defining horizontal and vertical polarization, respectively, k_1 and k_2 are the real and imaginary parts of the relative complex dielectric constant, respectively, and $\mu = \cos\theta$ where θ is the incidence angle relative to nadir. The parameters p and q are given by:

$$p = \frac{1}{\sqrt{2}} \left\{ \left[(k_1 + \mu^2 - 1)^2 + k_2^2 \right]^{1/2} + (k_1 + \mu^2 - 1) \right\}^{1/2}$$

$$q = \frac{1}{\sqrt{2}} \left\{ \left[(k_1 + \mu^2 - 1)^2 + k_2^2 \right]^{1/2} - (k_1 + \mu^2 - 1) \right\}^{1/2}$$

For a smooth surface, the emissivity is defined as:

$$\epsilon_i = 1 - R_i \; ; \qquad i = h \text{ or } v \qquad (3)$$

Although most natural earth surfaces (excluding calm water) are not electromagnetically smooth at microwave frequencies, the dependence of R on soil moisture (through k_1 and k_2) can be used as a guide in the study of the response of microwave sensors to soil moisture.

2.2 Skin Depth

The energy received by a microwave radiometer viewing a given target is composed of contributions from the target surface as well as sub-surface layers. Similarly, the backscattered energy (in the case of active microwave sensors) is also depth dependent. The penetration of microwaves into a medium is defined by the attenuation coefficient of the medium, which in turn is a function of its dielectric properties:

$$\alpha = \frac{2\pi}{\lambda} \left[\frac{k_1}{2} \left[\left(1 + \left(\frac{k_2}{k_1} \right)^2 \right)^{1/2} - 1 \right] \right]^{1/2} \qquad (4)$$

where

α = attenuation coefficient, nepers/m ;

λ = wavelength, m;

k_1 , k_2 = real and imaginary parts of the relative dielectric constant of the medium.

In the above expression, the relative magnetic permeability was assumed to be unity, which is a good approximation at microwave frequencies for most natural surfaces including water.

At a depth h beneath the surface, the power is related to the surface value P(o) by:

$$P(h) = P(o)\ e^{-2\alpha h} \tag{5}$$

At a depth δ such that $\alpha\delta = 1$, $\frac{P(h)}{P(o)} = 0.13$. δ is defined as the skin depth. Reflections from a plane δ deep by a perfect reflector will undergo additional attenuation by the same amount, thereby arriving at the surface having a magnitude that has been reduced to $\simeq 0.017$. If the medium depth profile of k_1 and k_2 is not a constant, then δ can be defined by:

$$\int_0^{\delta} \alpha\, dh = 1 \tag{6}$$

3.0 DIELECTRIC PROPERTIES OF SOILS

For naturally occurring substances, dielectric constant measurements in the microwave region are usually not repeatable by different investigators (Edgerton, et al., 1971, Ward et al., 1969). Dielectric measurements of soils require high precision and are time-consuming because of the number of factors that affect soil dielectric behavior (Poe et al., 1971). Furthermore, since adequate techniques are available only in the laboratory, preparation of samples for measurements involves a profound disturbance of the mutual arrangements of soil aggregates. It is not certain to what extent the laboratory-prepared samples are representative of soils as they exist in the field. However, since no better data are available, these measurements are continually used for interpretation of remote sensing data.

The dependence of the dielectric constant has been studied as a function of several parameters: moisture, bulk density, soil type, temperature, and frequency. These effects are discussed in the following sections.

3.1 Moisture

For soil dielectric constant measurements, soil moisture is usually expressed on a weight basis (i.e., gravimetrically):

$$m_w = \frac{W_w}{W_d} \times 100 \qquad (\%) \qquad (7)$$

where

m_w = moisture content by dry weight (%);
W_w = weight of water in the sample (g);
W_d = weight of dry soil in the sample (g).

Lundien (1971) suggested that moisture content expressed on a volume basis may be preferrable because data plotted against the volumetric water content m_v should have little sensitivity to changes in bulk density or degree of soil compaction. The value of m_v may be calculated using the bulk density of soil sample ρ_s and the density of water ρ_w:

$$m_v = \frac{W_w \cdot \rho_s}{W_d \cdot \rho_w} \qquad (\text{grams/cm}^3) \qquad (8)$$

When soil moisture is expressed on a weight basis, it is possible for two soils to contain the same water content in percent by weight while the actual amounts of water differ. For example, a 30% moisture content represents both 0.36 g of water for bulk density of 1.2 g/cm^3 and 0.54 g for bulk density of 1.8g/cm^3 in 1 cm^3 of soil. It has been argued that the number of water molecules (i.e., dipole moments) per unit volume rather than the weight proportion determines the dielectric contribution of water (Hoekstra and Delaney, 1974). Formulas for calculating dielectric constants of mixtures are also based on volume fractions (Poe et al., 1971; Birchak et al., 1974). Consequently, soil water should be expressed in cm^3 or grams per 1 cm^3 of soil when related to soil dielectric properties. However, many soil dielectric constant measurements have been presented on a weight basis only. In this report, both data have been included.

Available studies show that the relative (with respect to vacuum) dielectric constant of soils increases with increasing moisture content. This is to be expected since the relative permittivity of dry soil is less than 5 while that of water can be more than an order of magnitude larger (Figure 1). Figures 2 through 15 contain measurements on the weight basis, and Figures 17 through 24 show dielectric constant as a function of water expressed in grams per cm^3. The data are divided according to frequency and soil texture (i.e., relative proportions of soil particles of different sizes). The following observations can be made.

(1) Few of the measurements were taken for moisture contents near 0 per cent. Results of Matzler (1970, Figure 12) and Geiger and Williams (1972, Figure 14) show a tendency toward sharp increase in the real part of the dielectric constant k_1 for this moisture content range. Matzler (1970) suggested that such increase may be due to chemical changes resulting from addition of water, such as hydration. From the remote sensing standpoint, these changes are not very important since under natural conditions, dry soil always contains some water. For example, the amount of hygroscopic water (i.e., soil water held mostly by soil colloids under tensions above approximately 31 atmospheres so that it is unavailable to plants) was found to be 3.4% for a sandy soil and 16.1% for a silty clay (Russell, 1939).

(2) At low moisture contents, k_1 increases slowly (Figures 2, 4, 8, 10) or remains constant (Figures 6, 12). Lundien (1971) and Wiebe (1971) explained this phenomenon by the adsorption of water at the surface of fine particles; the adsorbed water has a limited mobility (similar to water molecules bound in ice) and consequently its dielectric constant can be as low as 0.1 that of free water (Grim, 1968). The possibility that

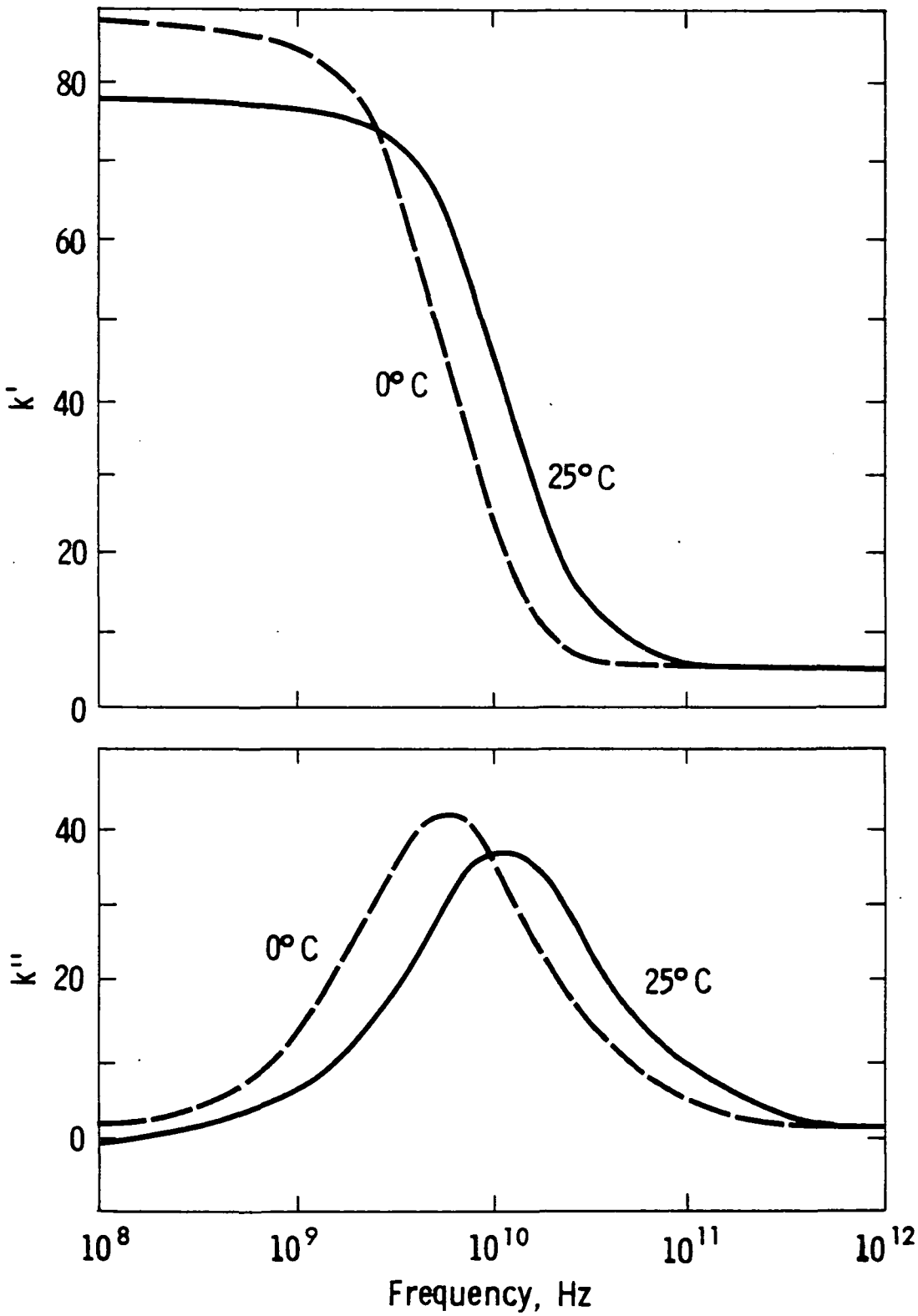

Figure 1. The dielectric spectrum of water at two temperatures. (From Hoekstra and Delaney (1974)).

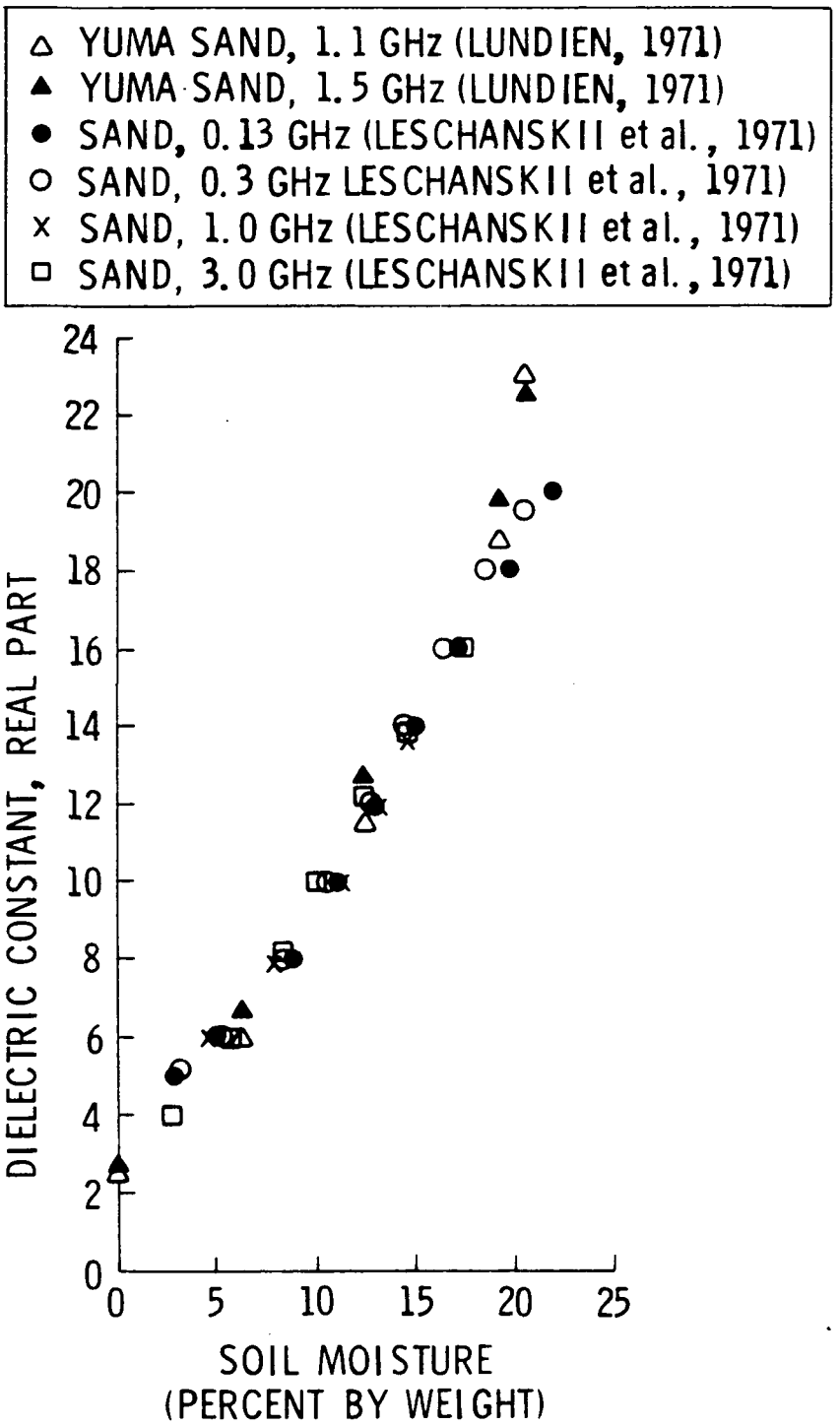

Figure 2. Relative dielectric constant values of soil as a function of gravimetric water content: Sand; frequency 0.13 GHz - 3.0 GHz; real part.

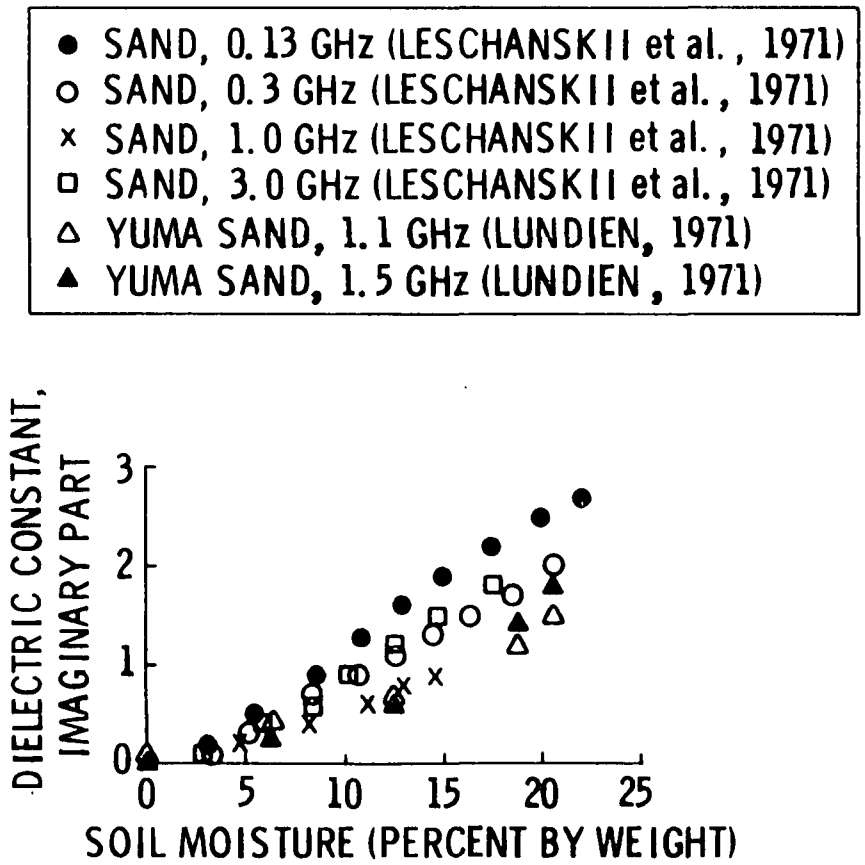

Figure 3. Relative dielectric constant values of soil as a function of gravimetric water content: Sand; frequency 0.13 GHz - 3.0 GHz; imaginary part.

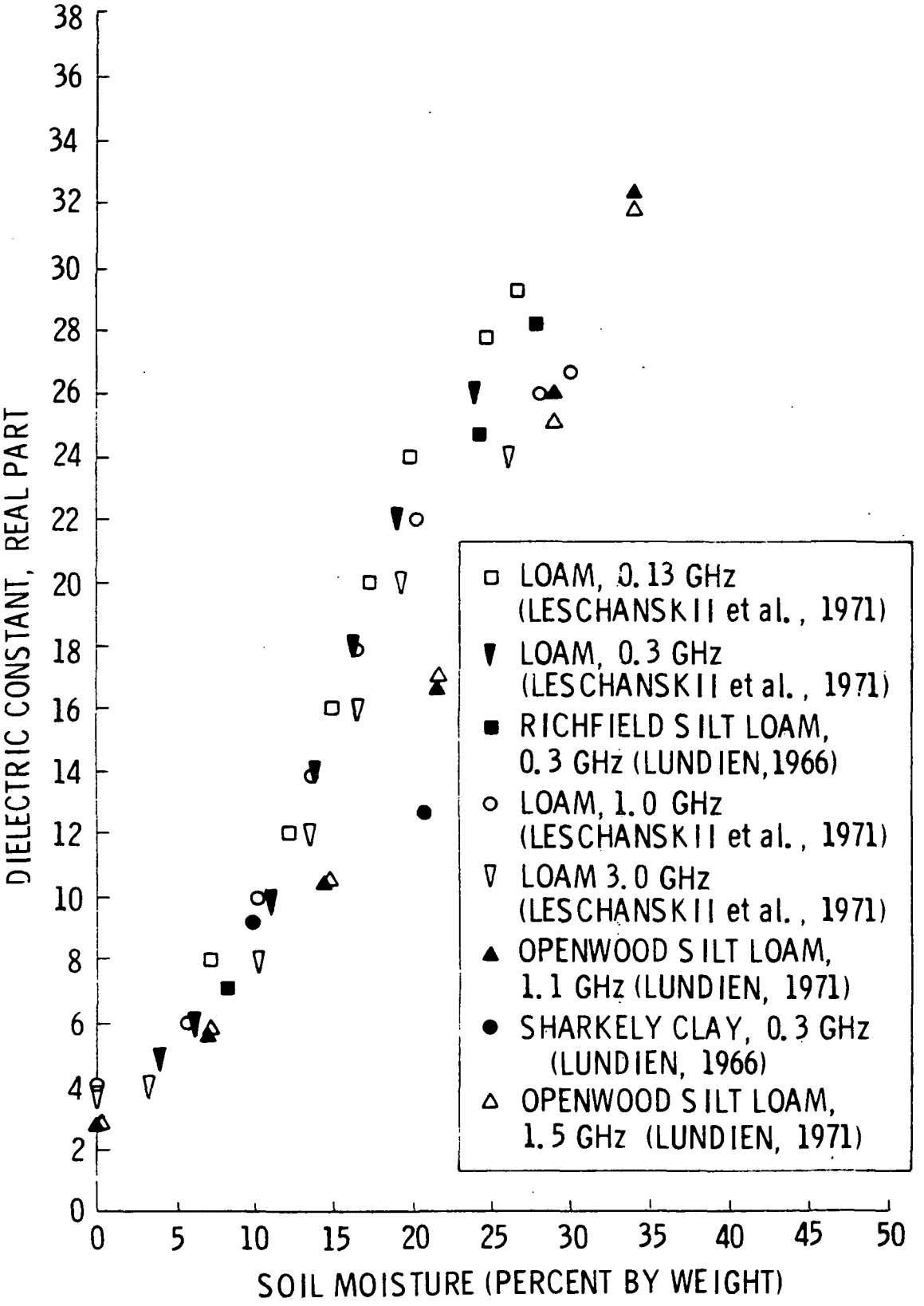

Figure 4. Relative dielectric constant values of soil as a function of gravimetric water content: Loam; frequency 0.13 GHz - 3.0 GHz; real part.

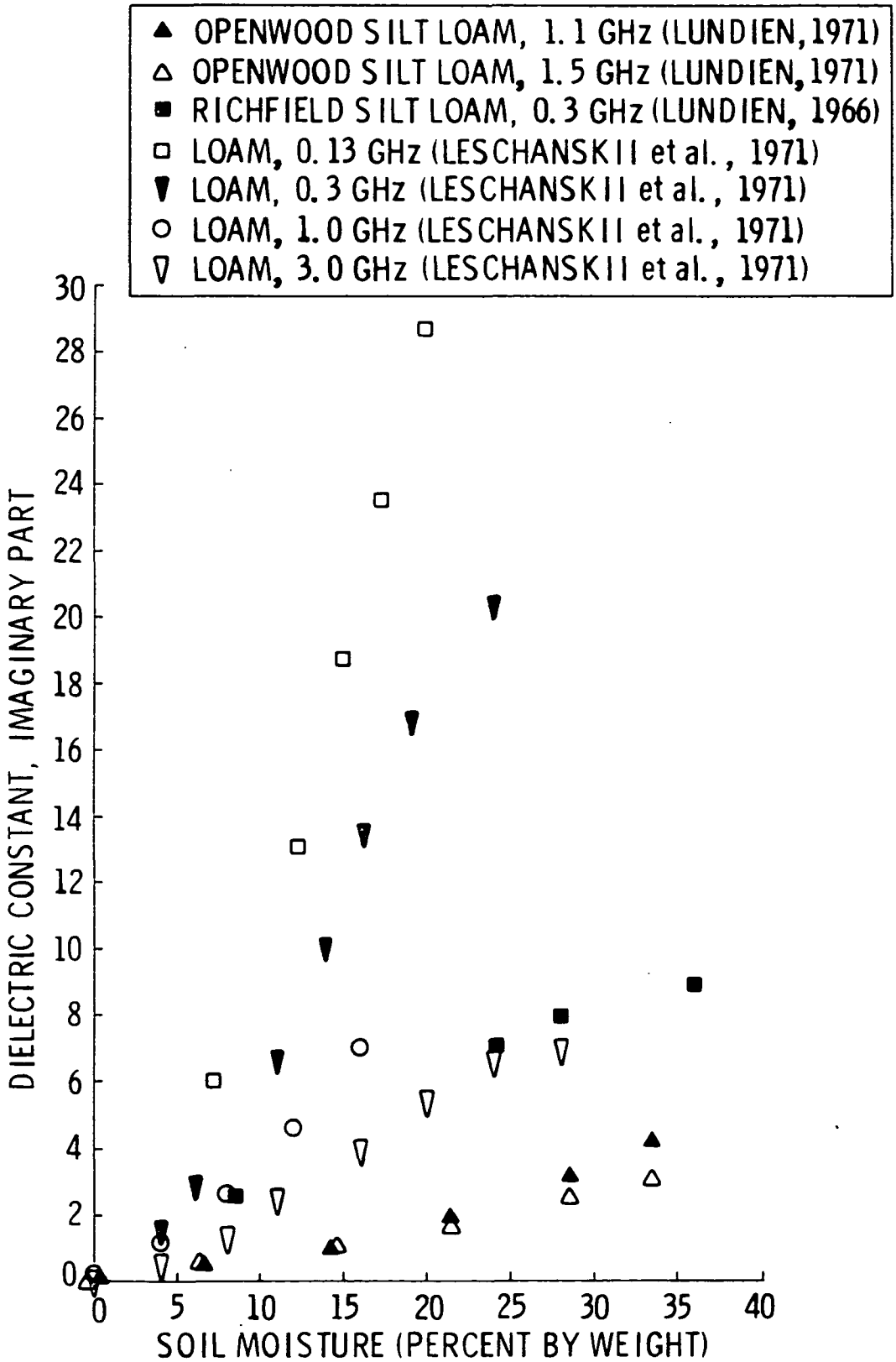

Figure 5. Relative dielectric constant values of soil as a function of gravimetric water content: Loam; frequency 0.13 GHz - 3.0 GHz; imaginary part.

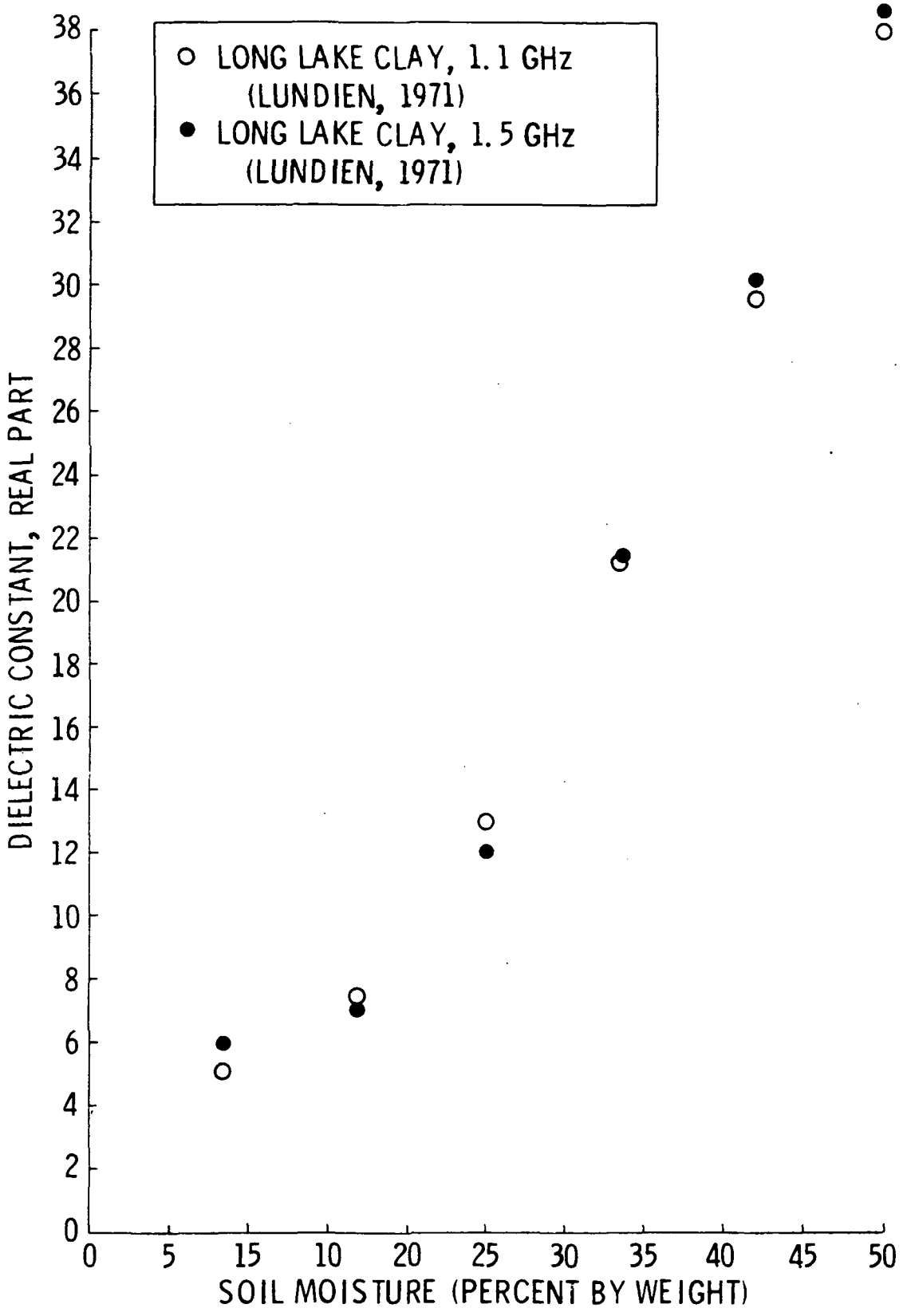

Figure 6. Relative dielectric constant values of soil as a function of gravimetric water content: Clay; frequency 1.1 GHz - 1.5 GHz; real part.

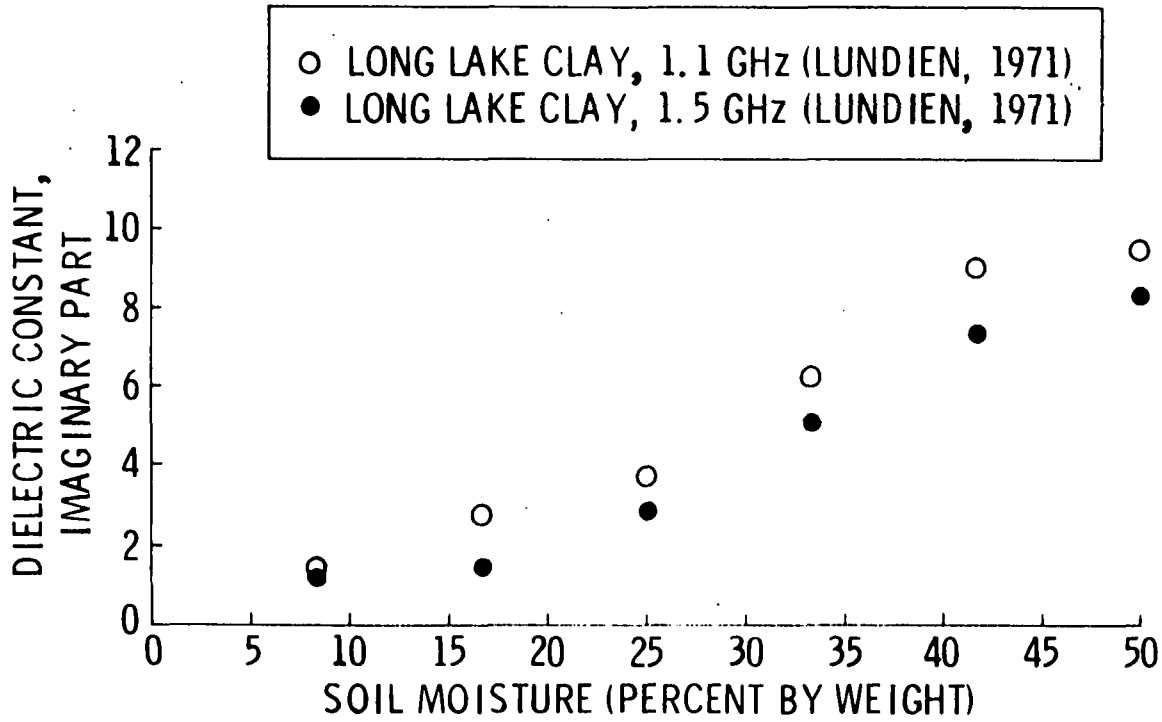

Figure 7. Relative dielectric constant values of soil as a function of gravimetric water content: Clay; frequency 1.1 GHz - 1.5 GHz; imaginary part.

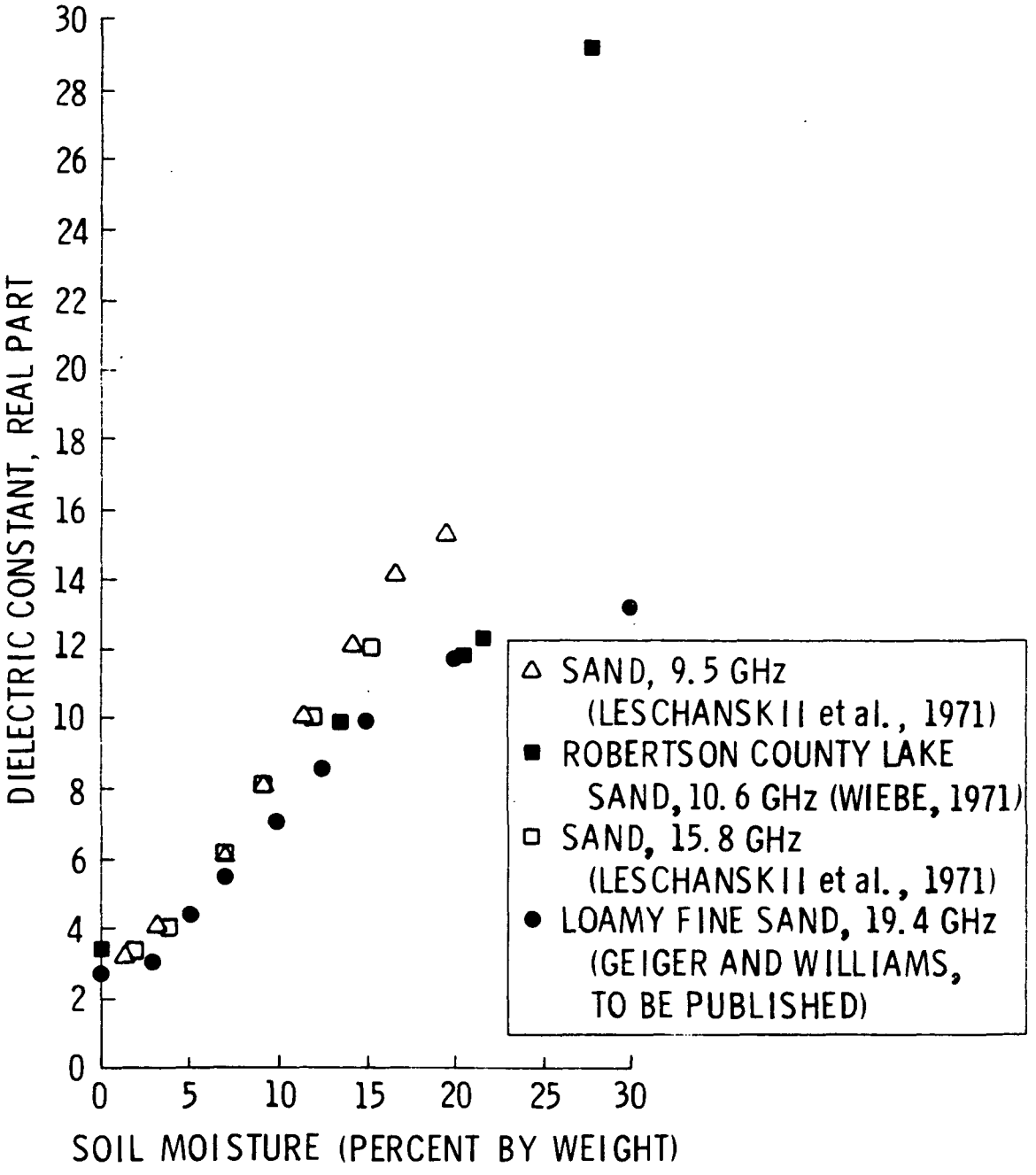

Figure 8. Relative dielectric constant values of soil as a function of gravimetric water content: Sand; frequency 9.5 GHz - 19.4 GHz; real part.

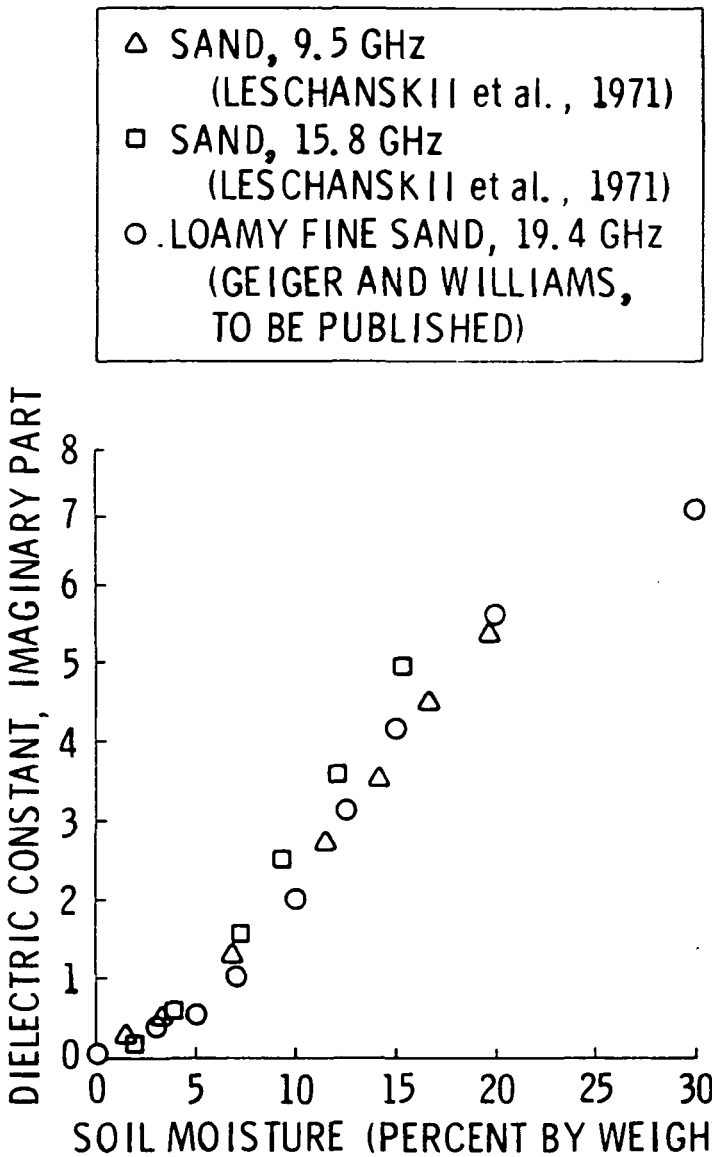

Figure 9. Relative dielectric constant values of soil as a function of gravimetric water content: Sand; frequency 9.5 GHz - 19.4 GHz; imaginary part.

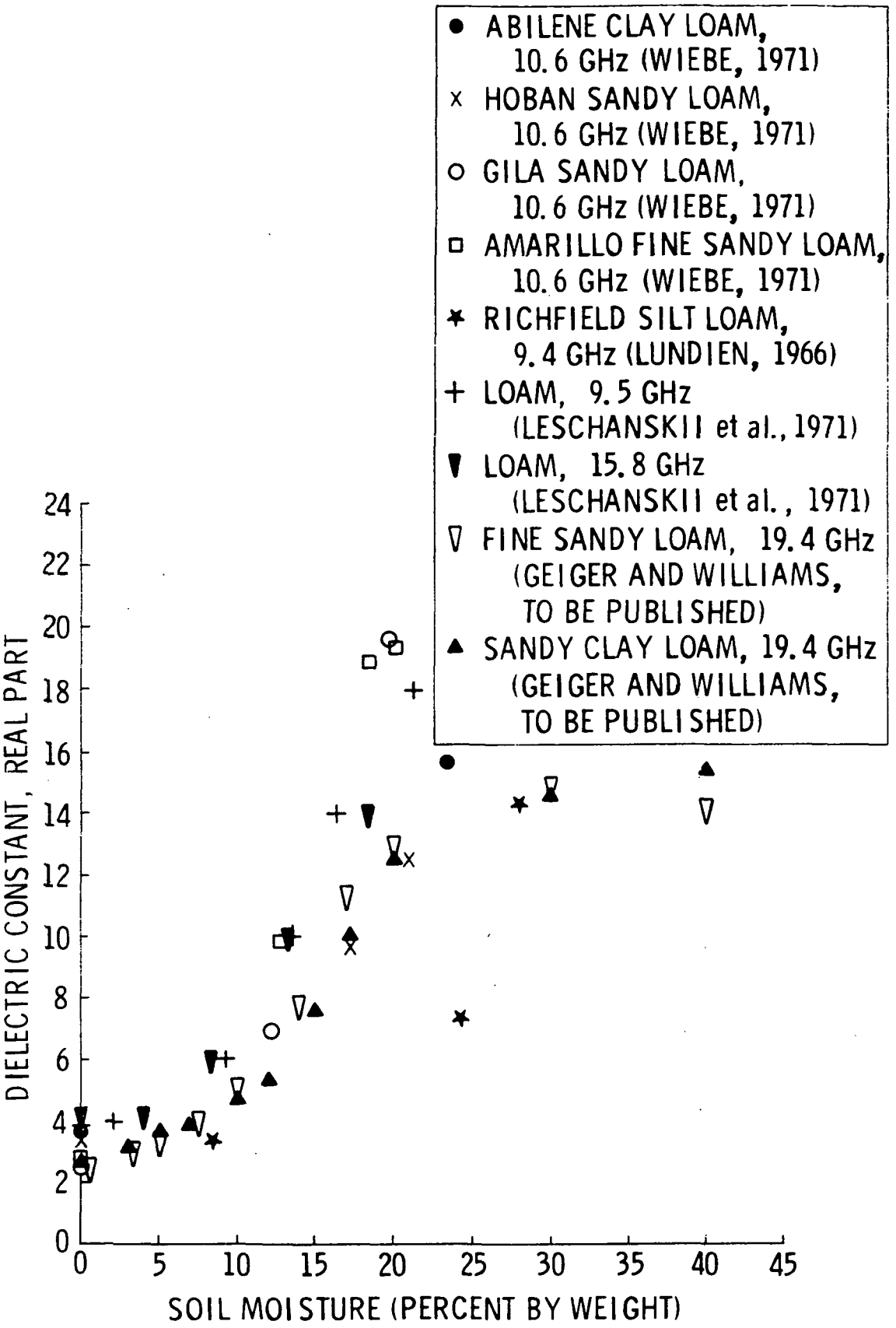

Figure 10. Relative dielectric constant values of soil as a function of gravimetric water content: Loam; frequency 9.4 GHz - 19.4 GHz; real part.

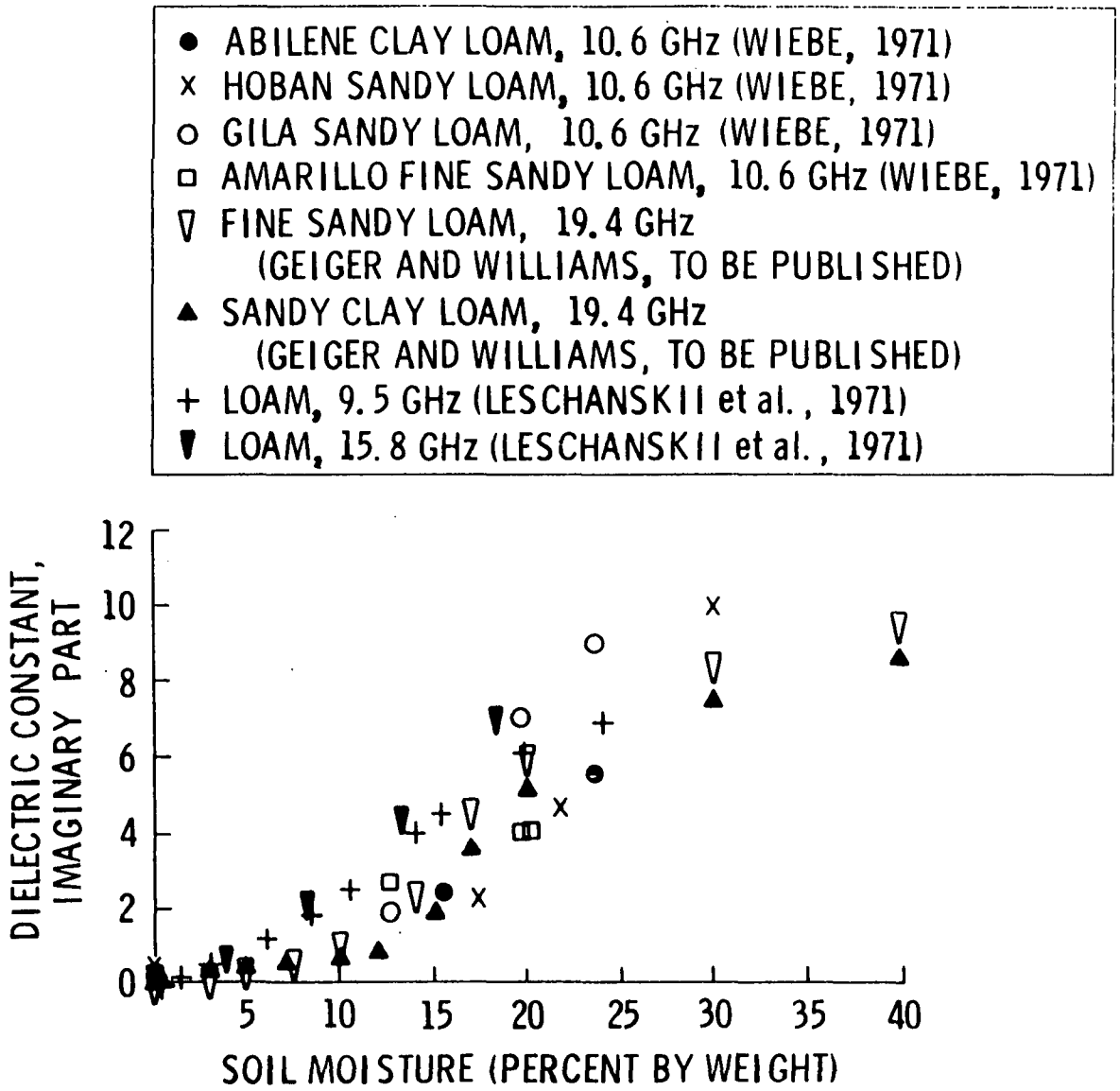

Figure 11. Relative dielectric constant values of soil as a function of gravimetric water content: Loam; frequency 9.5 GHz - 19.4 GHz; imaginary part.

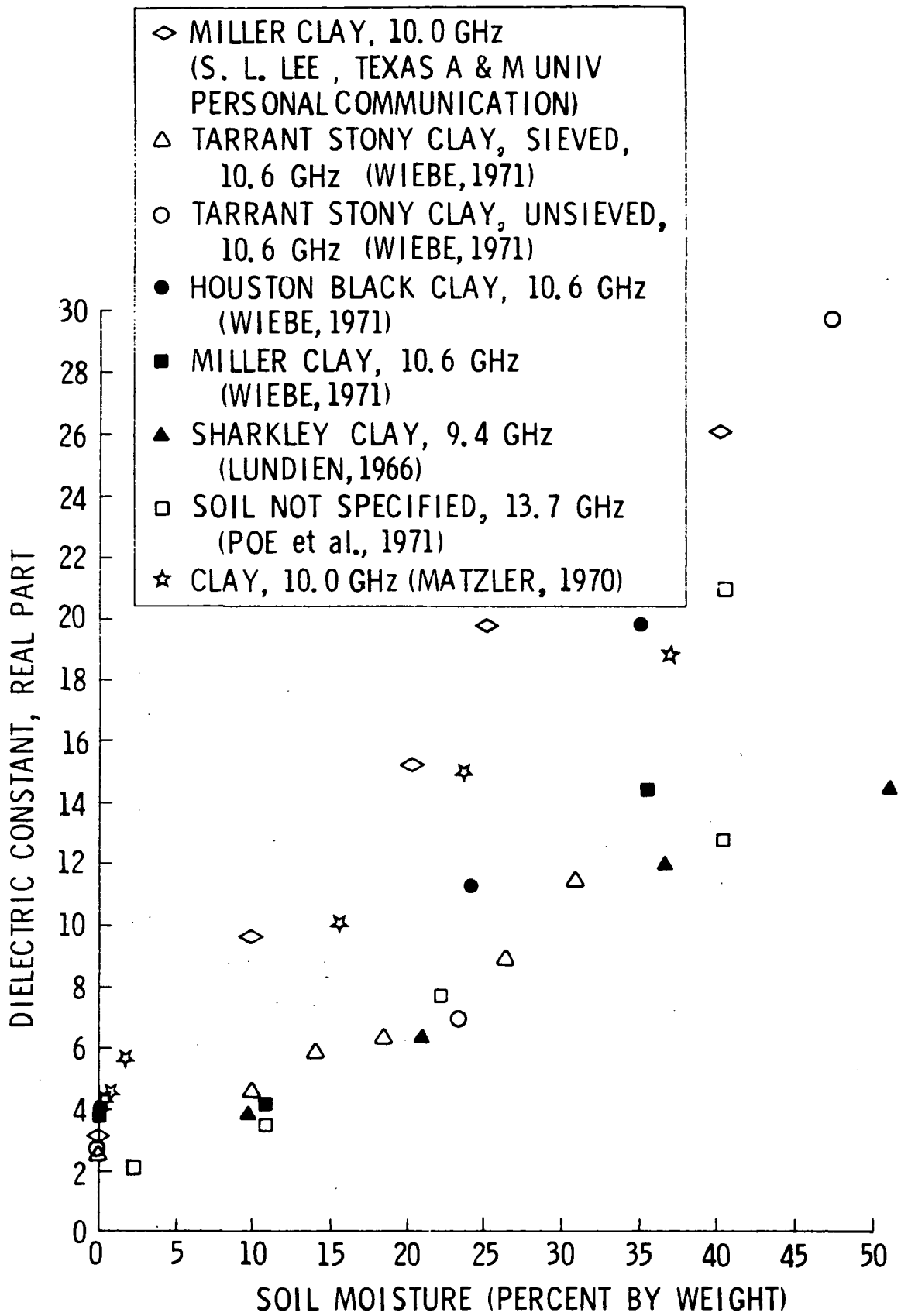

Figure 12. Relative dielectric constant values of soil as a function of gravimetric water content: Clay; frequency 9.4 GHz - 13.7 GHz; real part.

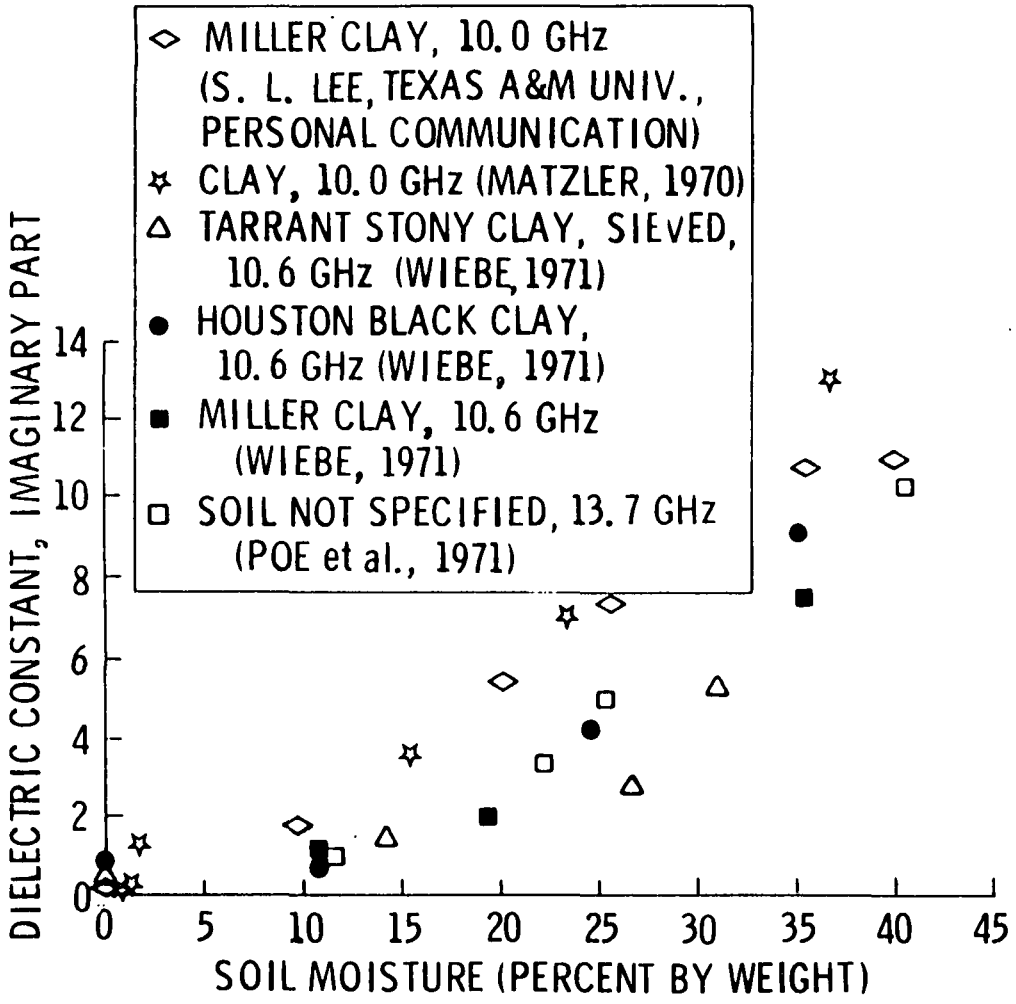

Figure 13. Relative dielectric constant values of soil as a function of gravimetric water content: Clay; frequency 10.0 GHz - 13.7 GHz; imaginary part.

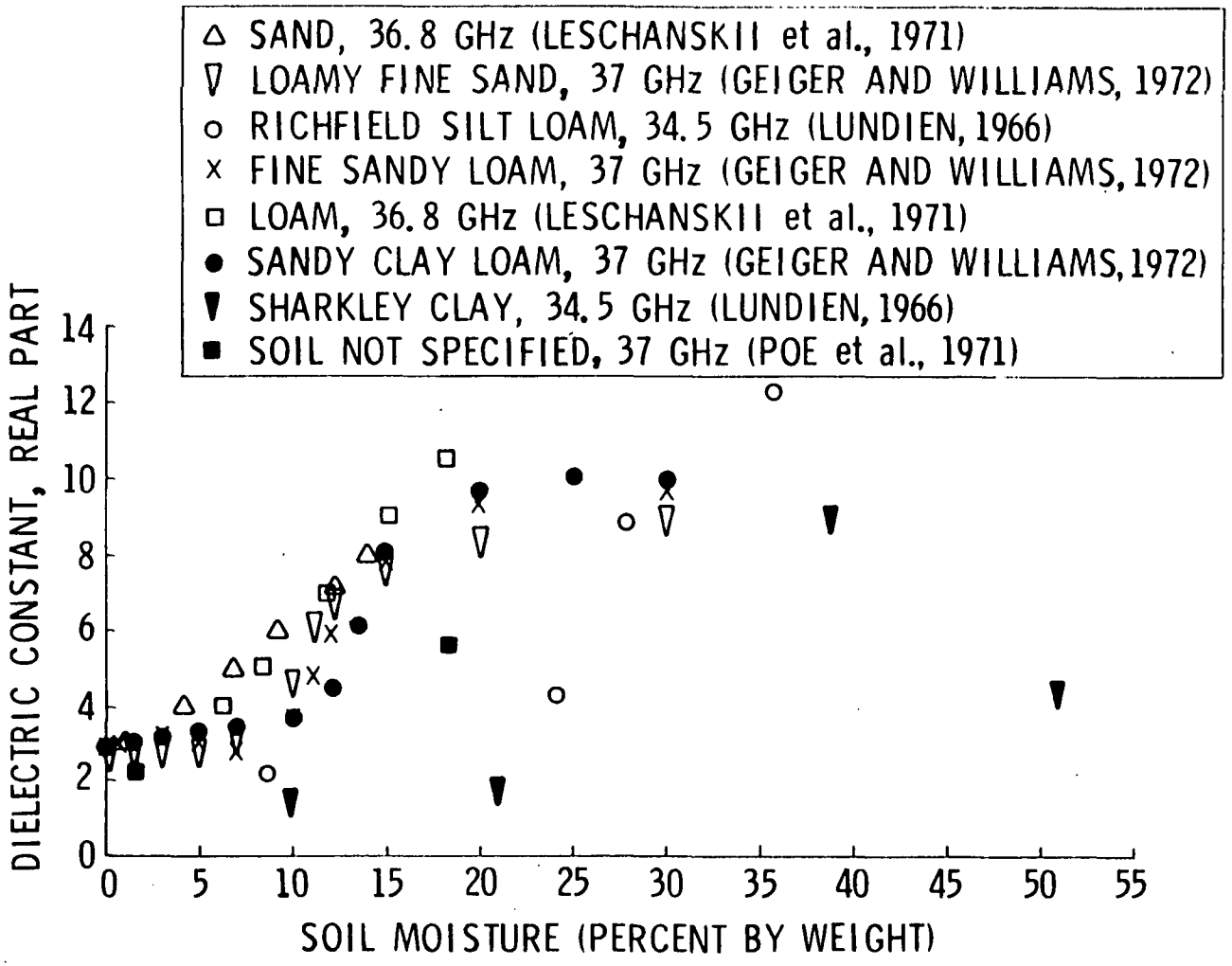

Figure 14. Relative dielectric constant values of soil as a function of gravimetric water content: Sand, loam, clay; frequency 34.5 GHz - 37 GHz; real part.

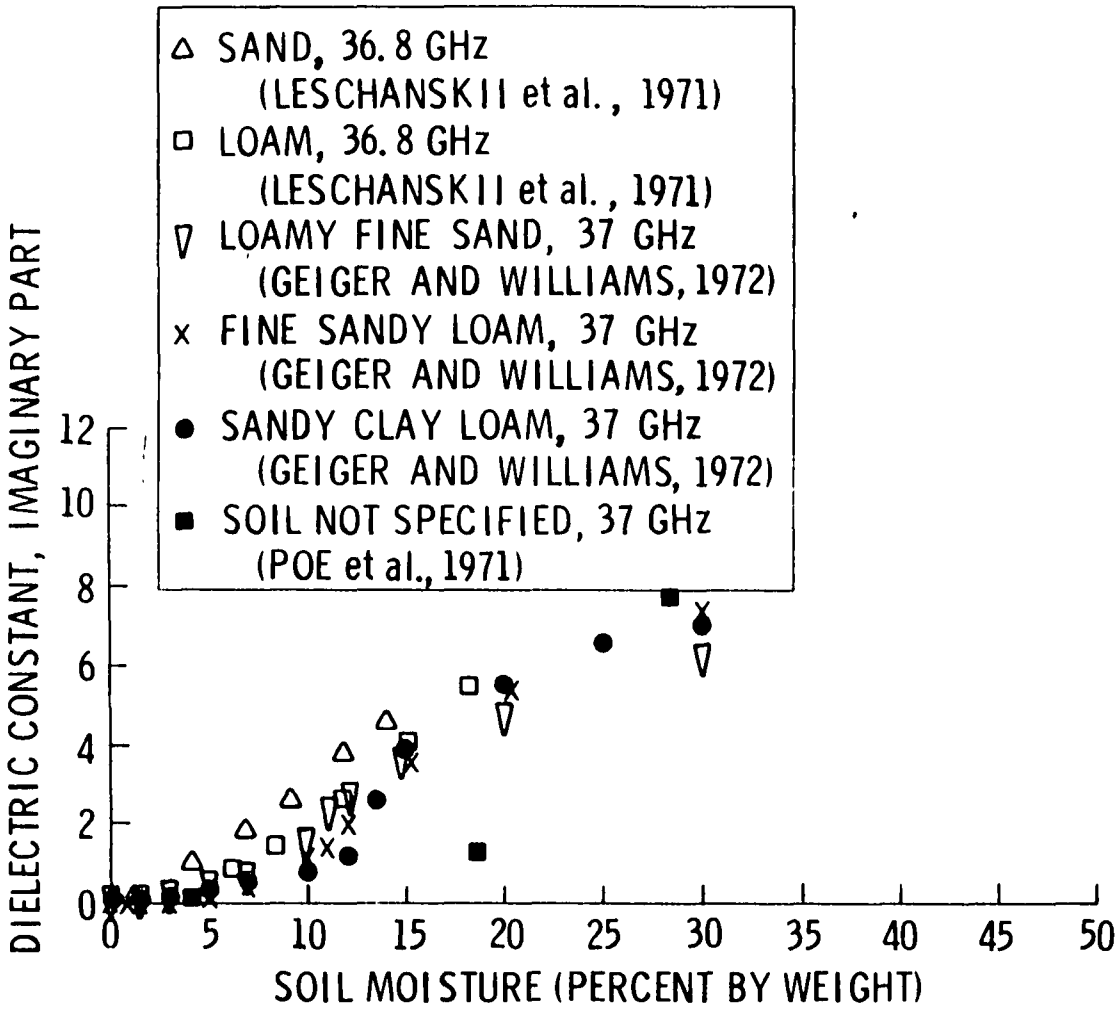

Figure 15. Relative dielectric constant values of soil as a function of gravimetric water content: Sand, loam, clay; frequency 34.5 GHz - 37 GHz; imaginary part.

soil dielectric constant is affected mostly by the loosely held water is of potentially great practical importance since only the water held with sufficiently small strength is available to plants. These relations should affect data in Figures 2 to 14 in the following ways:

(i) The range in which k_1 changes slowly with increasing moisture content should expand with increasing proportion of clay particles. Data in Figure 8, 10 and 12 (sand to clay in texture) indicate that this probably occurs but the measurements are not sufficiently detailed to establish the trend with certainty. Considering the range of the hygroscopic water contents between sand and clay mentioned above, one would expect the differences to be more pronounced. It should be noted that careful measurements by Geiger and Williams (1972, Figure 14) showed such a trend within a somewhat narrow textural range (loamy fine sand to sandy clay loam). Lundien (1971) also demonstrated this dependence using measurements at five frequencies between 1.074 GHz and 1.499 GHz.

(ii) As the proportion of fine particles increases, the k_1 curves should be shifted in the direction of higher moisture contents and should have less steep slopes. This is partly illustrated in Figures 2, 4, 6 and Figures 8, 10, 12, but a considerable overlap exists among various soils.

In the measurements presented on a volume basis (Figures 17 through 24), the above trends are not as apparent. For example, k values of Yuma sand and San Antonio clay loam near 1.0 GHz (Figure 19) are very similar. In addition, the values of k_1 appear to increase

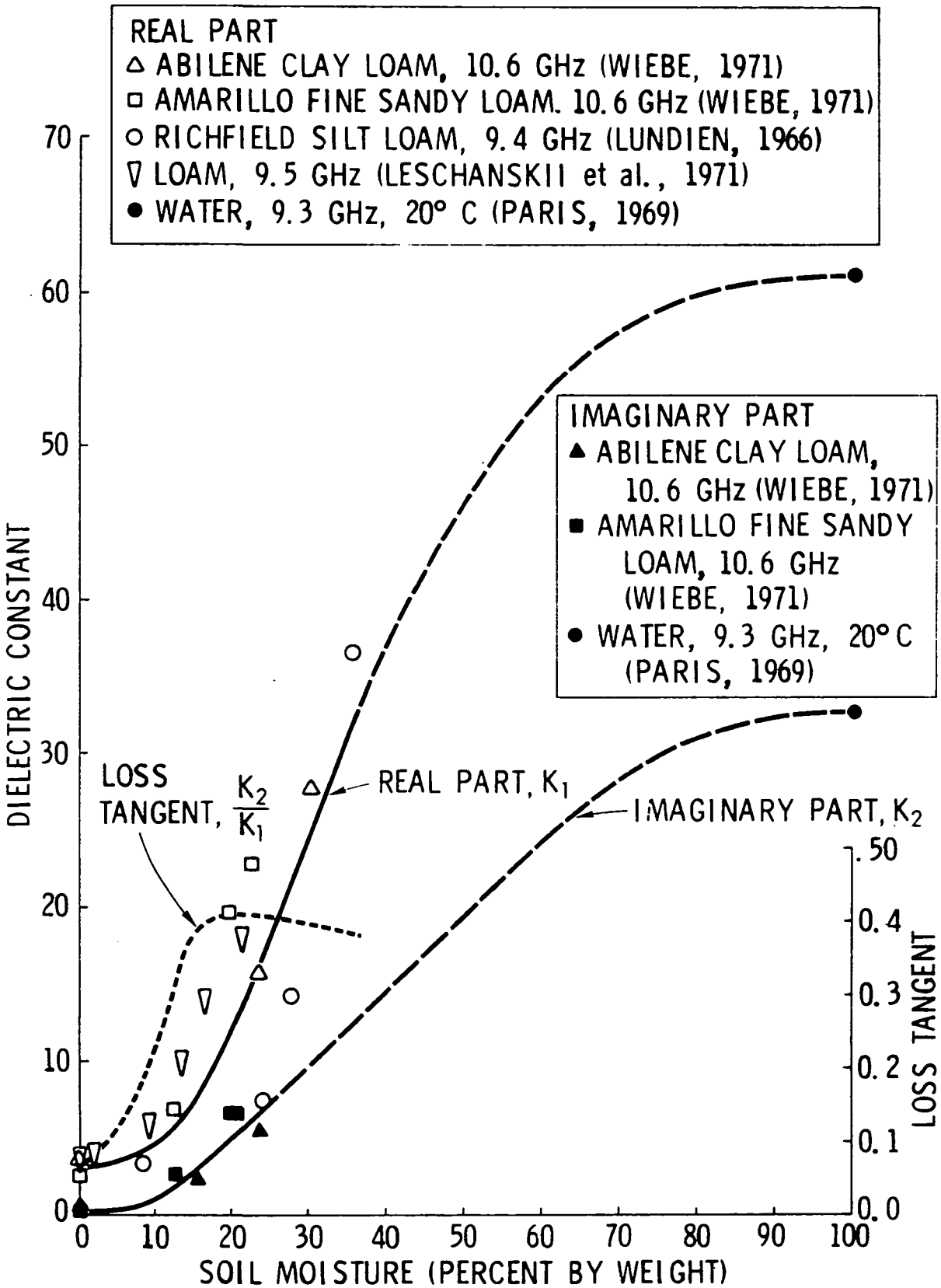

Figure 16. Measured dielectric constant data of loamy soils as a function of gravimetric water content around 10 GHz. Solid curves were drawn to fit the data points and the broken curves were extrapolated.

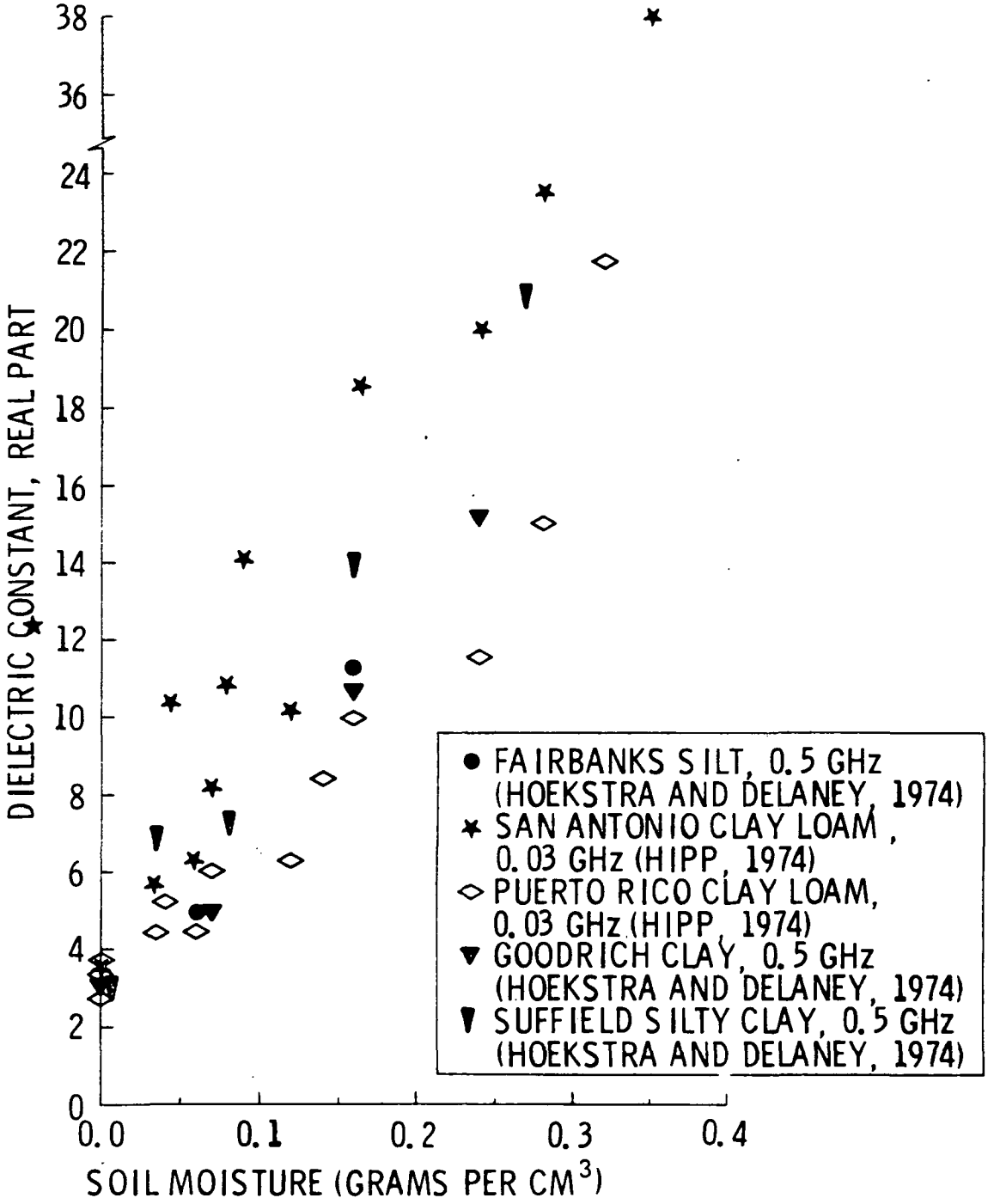

Figure 17. Relative dielectric constant values of soil as a function of volumetric water content: Loam, clay; frequency 0.03 GHz - 0.5 GHz; imaginary part.

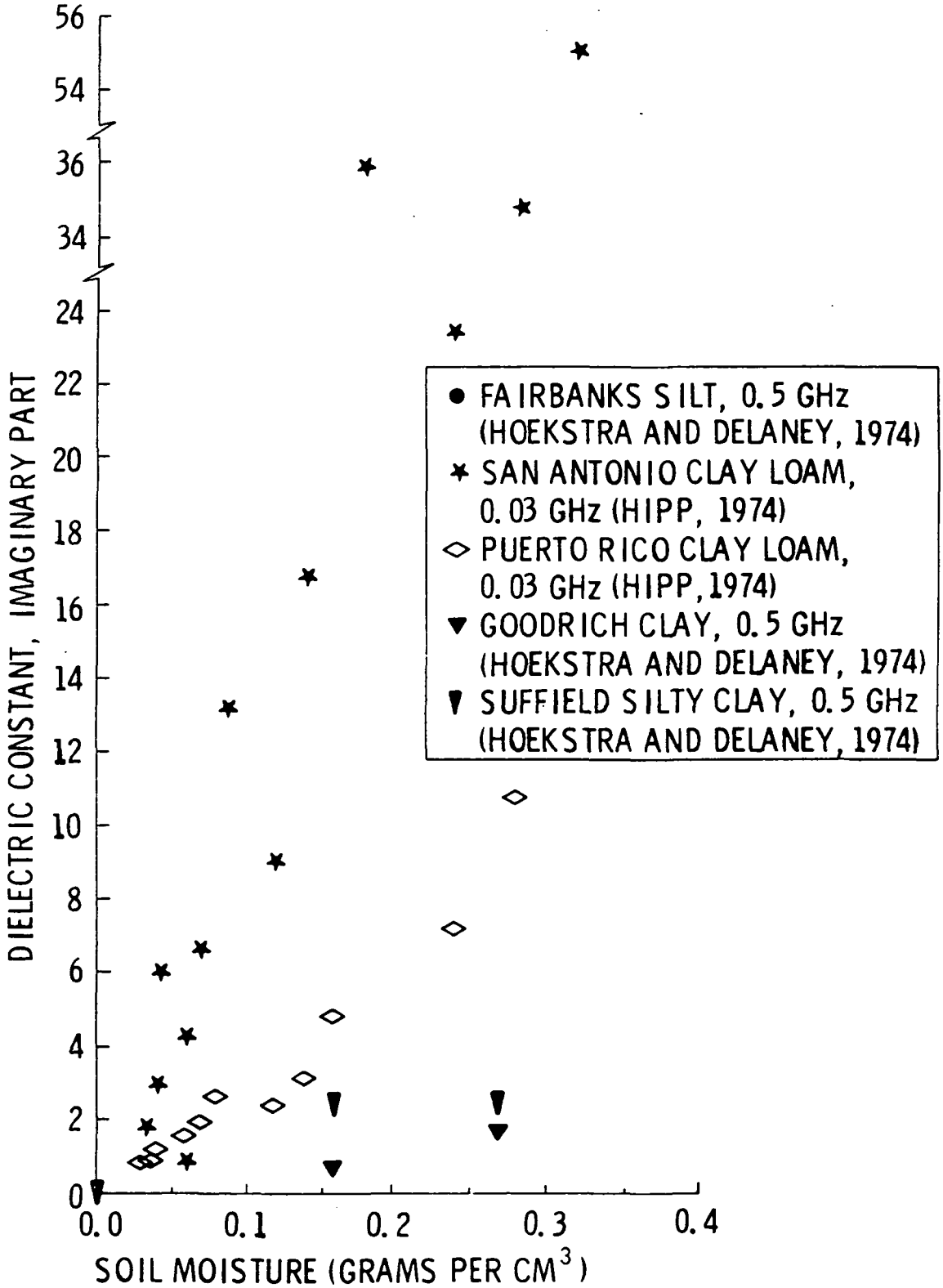

Figure 18. Relative dielectric constant values of soil as a function of volumetric water content: Loam, clay; frequency 0.03 GHz - 0.5 GHz; imaginary part.

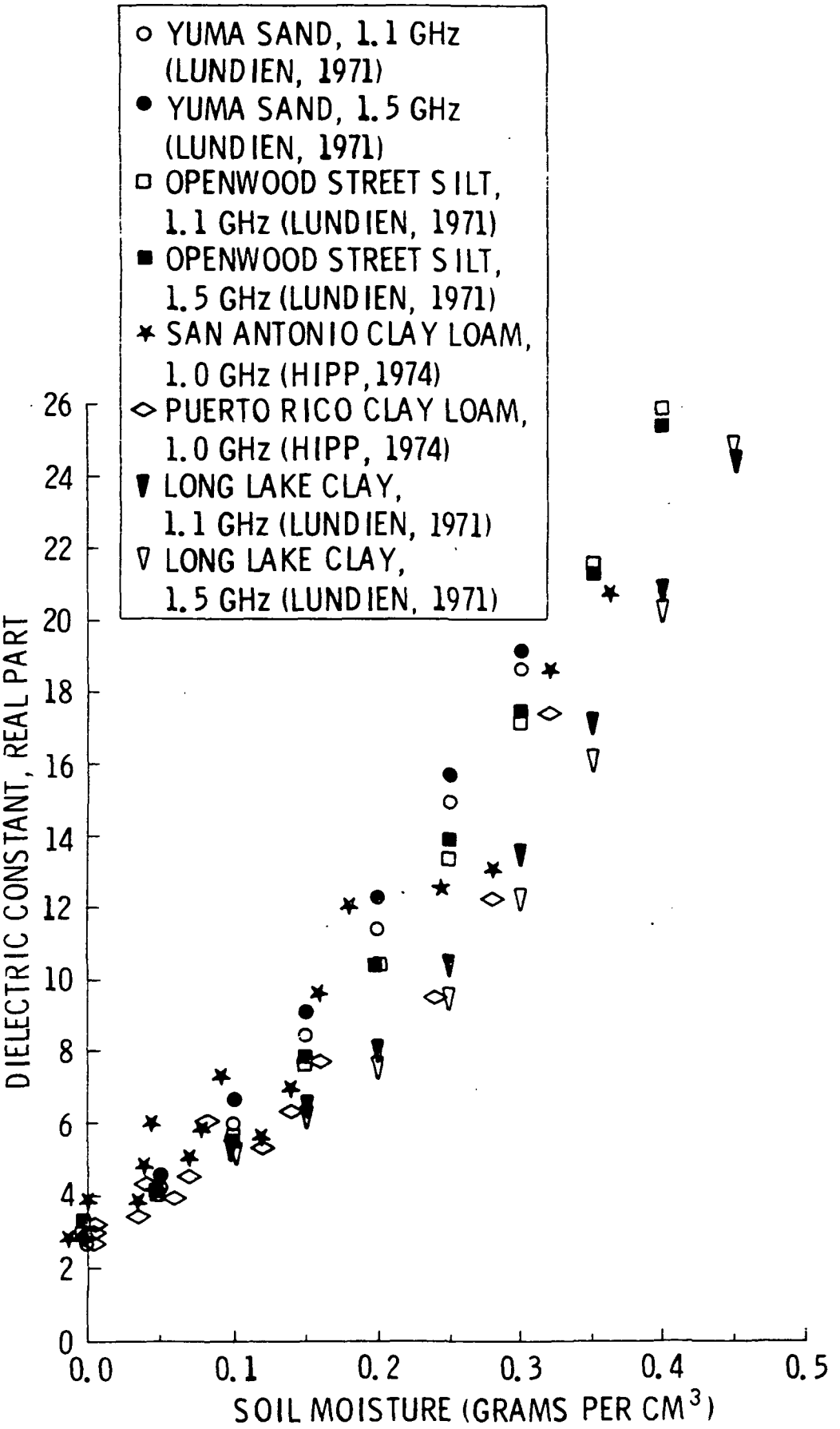

Figure 19. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 1.1 GHz - 1.5 GHz; real part.

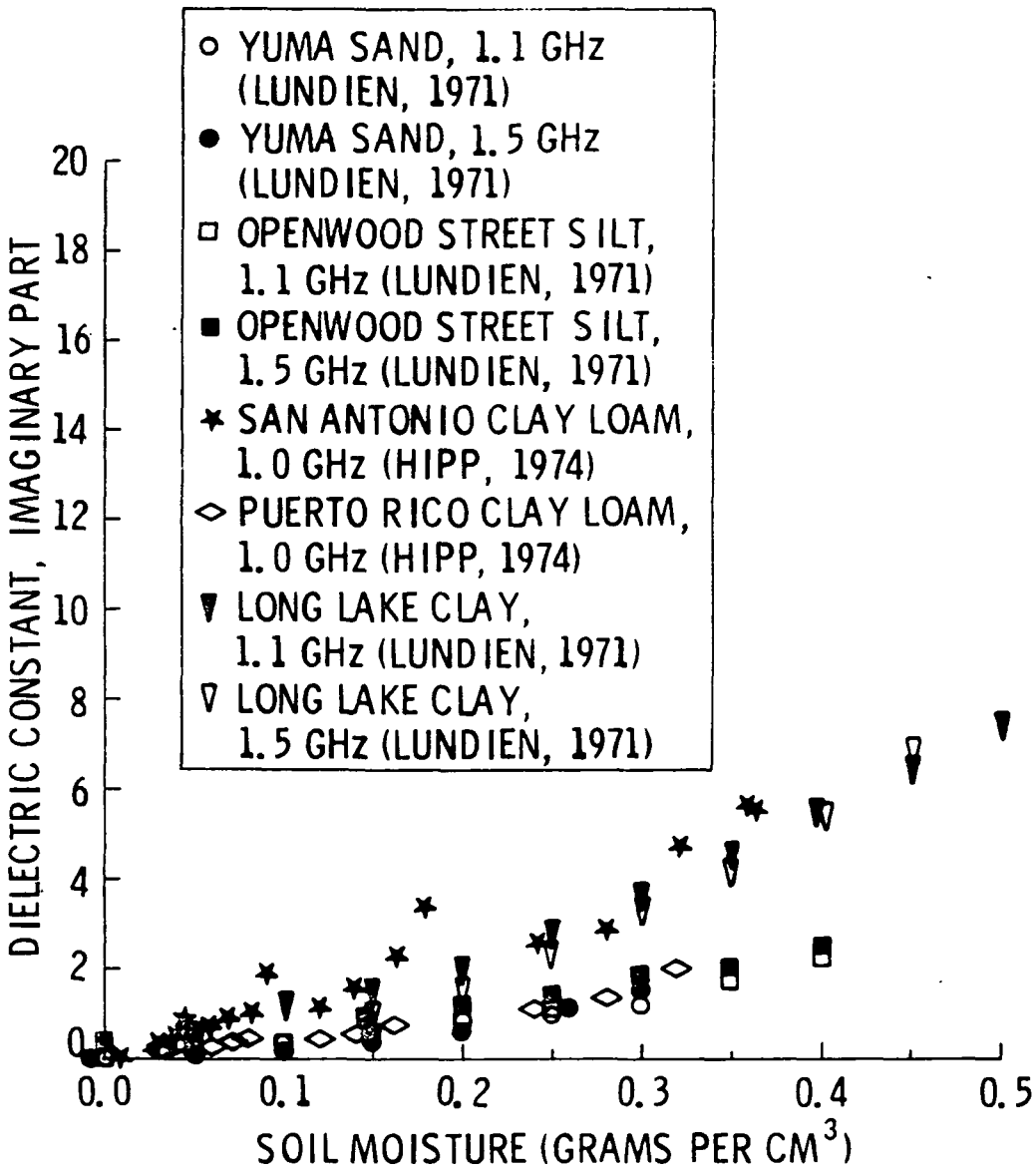

Figure 20. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 1.1 GHz - 1.5 GHz; imaginary part.

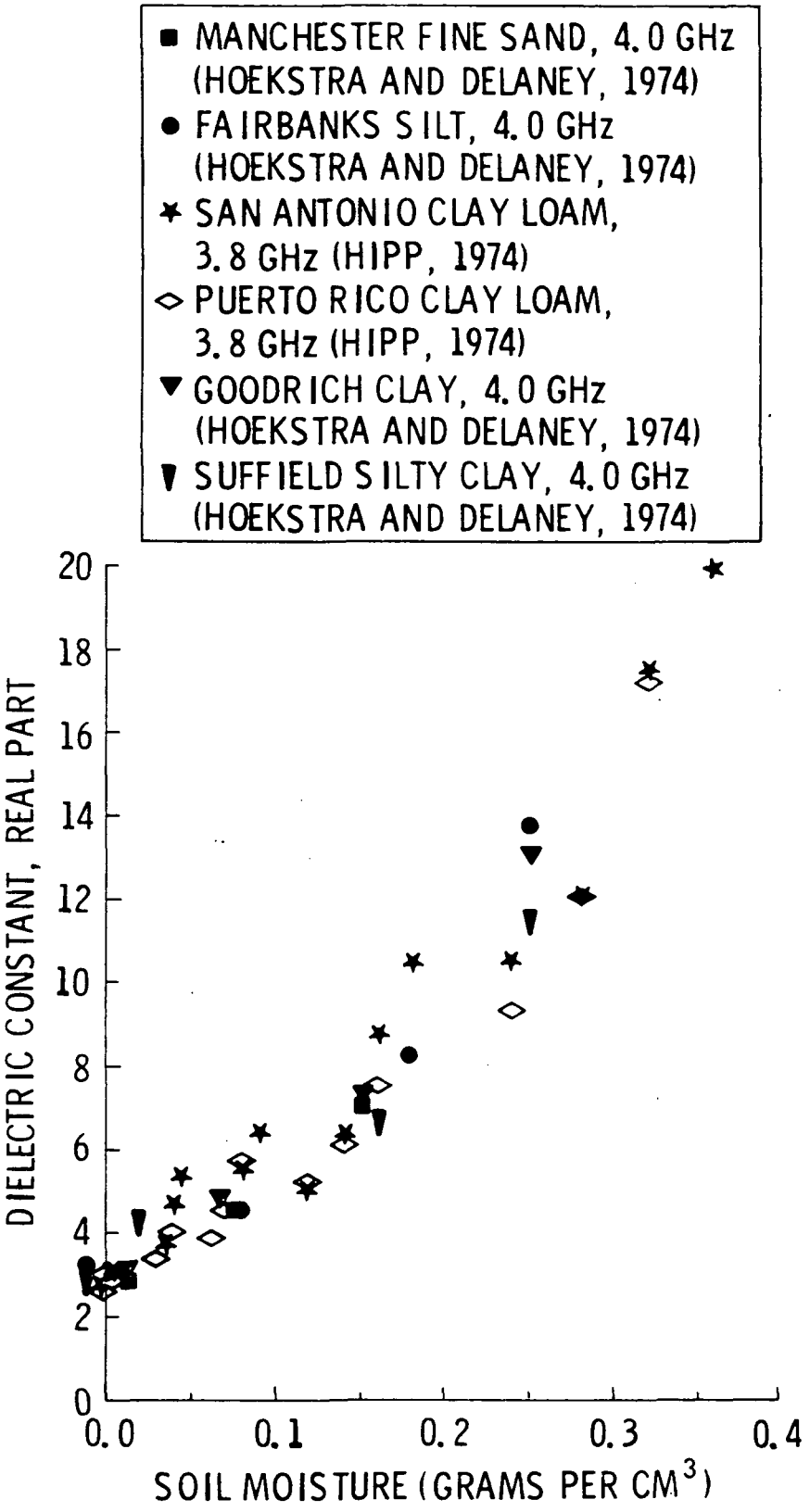

Figure 21. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 3.8 GHz - 4.0 GHz; real part.

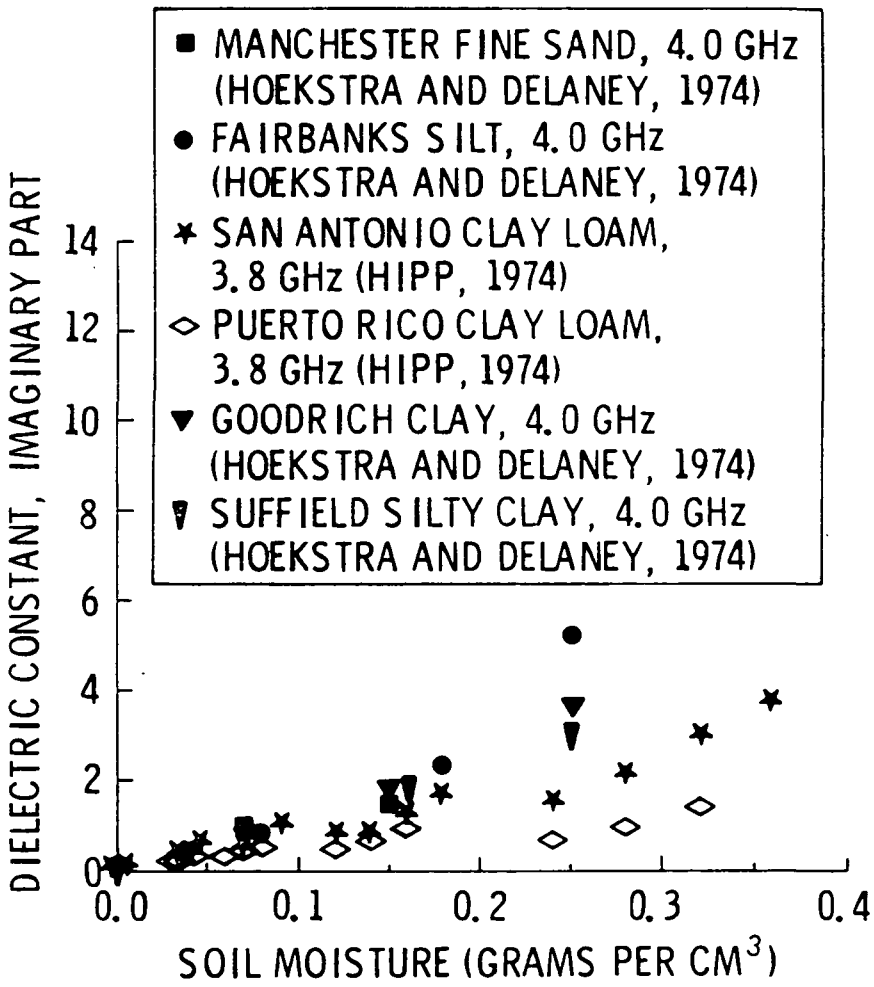

Figure 22. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 3.8 GHz - 4.0 GHz; imaginary part.

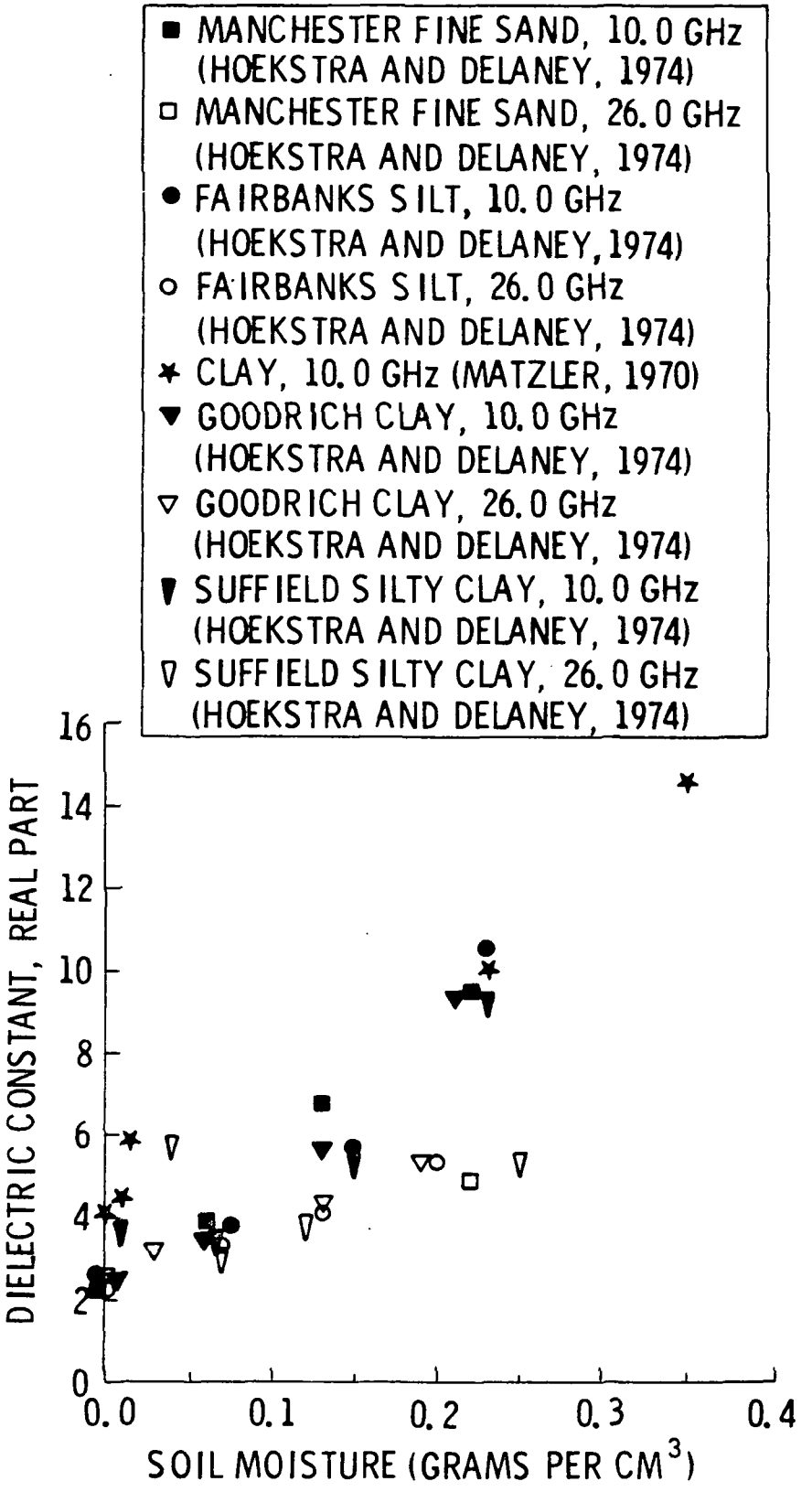

Figure 23. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 10.0 GHz - 26.0 GHz; real part.

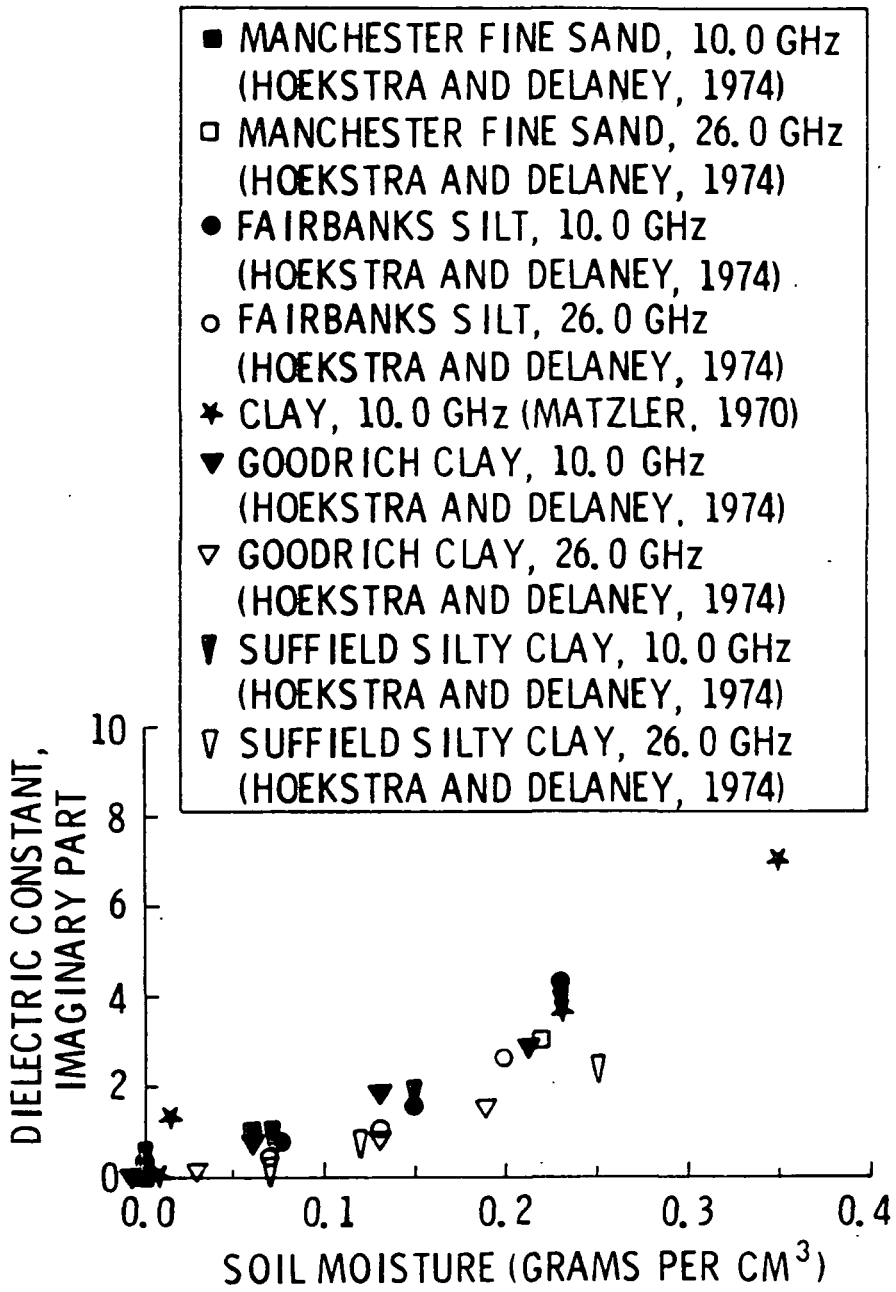

Figure 24. Relative dielectric constant values of soil as a function of volumetric water content: Sand, loam, clay; frequency 10.0 GHz - 26.0 GHz; imaginary part.

faster at low water contents than in Figures 2 to 14, and the effect of adsorbed water is not shown. Hoekstra and Delaney (1974) concluded that within the experimental error, the relaxation of water in sandy soils was identical to that in clay soils; this is also evident from data from Manchester fine sand, Fairbanks silt, and Goodrich clay (Figure 21).

To summarize, evidence regarding the effect of adsorbed water on the soil dielectric properties is not conclusive. Results of Lundien (1971), Geiger and Williams (1972), and Hipp (1974) suggests that within a given set of experimental conditions, such an effect may be shown if "proper" soils are used; the latter condition seems necessary because the dielectric constant has been found to differ for two soils of the same texture (San Antonio clay loam and Puerto Rico clay loam, 1.0 GHz, see Figure 19). The difference between soils of various textures appears smaller if the dielectric constant is expressed as a function of water content by volume. Consequently, before more conclusive results become available, the effect of adsorbed water on soil dielectric constant may be considered negligible in the 1 GHz to 35 GHz frequency range insofar as the interpretation of microwave remote sensing data is concerned.

(3) Values of k_1 should increase for higher moisture contents and ultimately should reach k_1 values of water at the measured frequency (Figure 1). Although soil dielectric constants are rarely measured at moisture contents above 40 per cent, the available data indicate trends toward the k_1 values of water. An exception is measurements by Geiger and Williams (Figures 8, 10, 14) which appear to level off at high moisture contents.

Figure 16 shows average curves for real and imaginary parts of the dielectric constant based on several measurements of loamy soils at frequencies near 10 GHz. The broken lines were drawn by extrapolating between experimental measurements and the dielectric constants of water. Assuming that the extrapolation is realistic, it can be seen that the real

part of the dielectric constant should increase nearly linearly at higher soil moisture content. Lundien's (1966, 1971) and Wiebe's (1971) measurements showed a similar relationship. However, k_1 values of Geiger and Williams, Leschanskii et al., (1971) and others tended to level off at higher moisture contents. The discrepancy has not yet been resolved; it is conceivable, however, that the soil/water mixing properties and the tendency for separation at higher moisture content could cause these differences. Another factor affecting the shape of these curves is bulk density. As discussed in Section 3.2 , the upper portions of the curves would shift to the right if moisture were measured in the volumetric units.

(5) The imaginary part of the dielectric constant k_2 was smaller at most frequencies than the real part and also increased monotonically with the increasing moisture content. Two exceptions to this trend were found. First, measurements of Geiger and Williams (Figures 9, 11, 15) showed an inflection point and were of the same order of magnitude as k_1 curves. Secondly, data of Leschanskii et. al., (1971) obtained at 0.13 GHz and 0.3 GHz exhibited relatively high k_2 values for loam (Figure 5); in the extreme case (0.3 GHz, 20% moisture) k_2 exceeded k_1. In contrast, k_2 values for sand were ten times smaller under otherwise identical conditions (Figure 3). This difference was explained by attenuating effect of ions present in the soil exchange complex; the amount of ions retained in loam is larger than in sand, and therefore attenuation is higher (Leschanskii et. al., 1971). The difference in attenuation was not detected at higher frequencies (centimeter wavelengths) because the attenuation by molecules of water predominates there and consequently the effect of soil material is obscured (Leschanskii et. al., 1971). Lundien (1971) also demonstrated that conductivity (which is directly proportional to k_2 at a given frequency) increased as the proportion of fine soil particles increased from sand to clay for frequencies between

1.074 GHz and 1.499 GHz. Figure 18 shows that k_2 was much higher at 0.03 GHz than at 0.5 GHz; no such difference was detected at higher frequencies for the same soils (Figure 22). Thus the ion exchange characteristics of soil material appear to affect soil dielectric properties at low frequencies. However, the magnitude of the effect at 0.3 GHz is more pronounced in the data reported by Leschanskii et al., (1971) (Figure 5) compared with Lundien's (1966, 1971). It should be noted that Hoekstra and Delaney (1974) did not detect any ionic interaction at 0.5 GHz.

The relationship between the relative dielectric constant and soil moisture has been quantified by Lundien (1971) for five frequencies (between 1.074 GHz and 1.499 GHz) in the following form:

$$m_v = \frac{k_1}{80} - \frac{0.26}{k_1 - 1} + 0.11 \quad \text{(grams per cm}^3\text{)} \qquad (9)$$

3.2 Bulk Density

Campbell and Ulrichs (1969) showed that the real part of the dielectric constant k_1 of rocks occupied a narrow range of values when the bulk density was constant (Figure 25). This range expanded considerably for the same rocks when samples with different bulk densities (constant porosity) were prepared (Figure 26). This difference could be due to either inherent dielectric properties of the various rocks or change in bulk density ρ_s. Figure 27 shows that k_1 increases with bulk density for a given soil type; consequently, bulk density of a given soil or rock material affects its dielectric constant. The curve in Figure 27 was calculated from Krotikov's (1962, in : Peake et al., 1966) formula:

$$k_1 = \left(1 + \frac{\rho_s}{2}\right)^2 \qquad (10)$$

Equation (10) was also found to hold for pumice at 10 GHz (Peake et al., 1966). The trend shown in Figure 27 is supported by results of Edgerton et al., (1971) who noticed a decrease in dielectric constant with decreasing bulk density for low moisture contents.

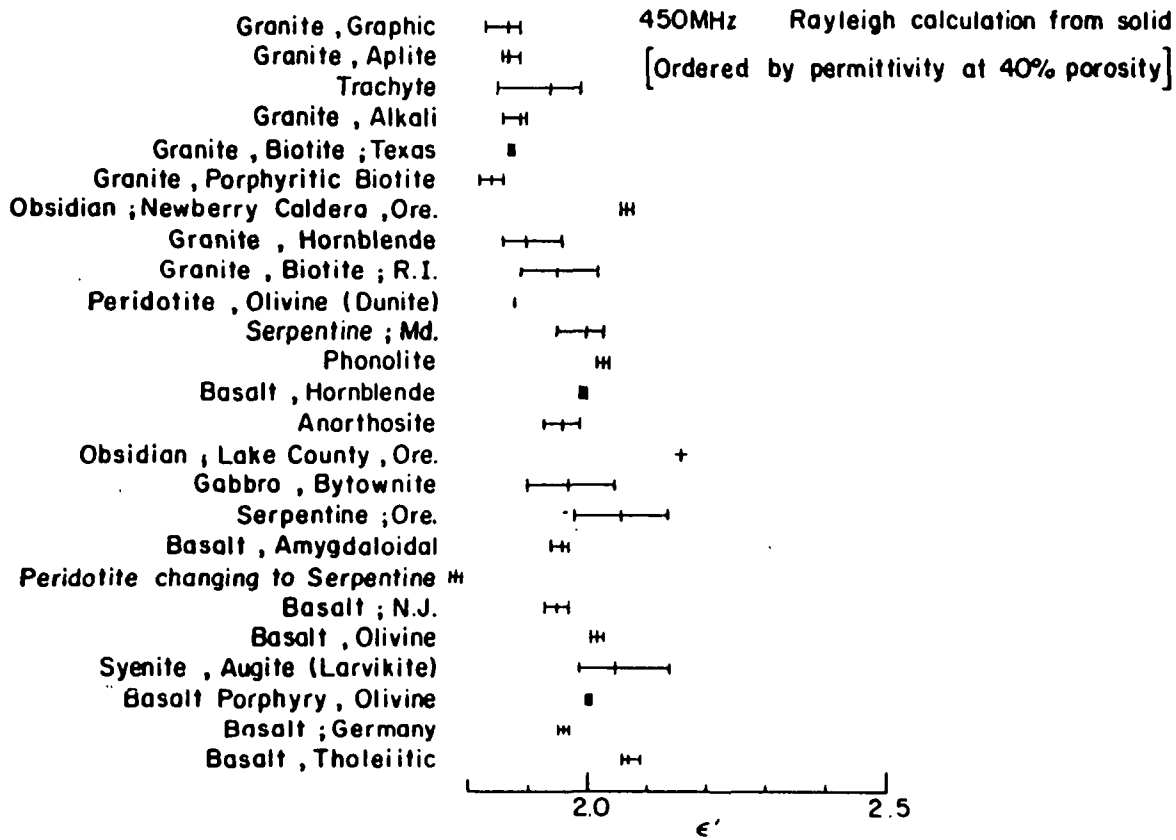

Figure 25. The permittivities of powdered rocks at a density of 1.0 g/cm^3, showing the mean, and maximum and minimum values as derived from solid rocks. (From Campbell and Ulrichs (1969)).

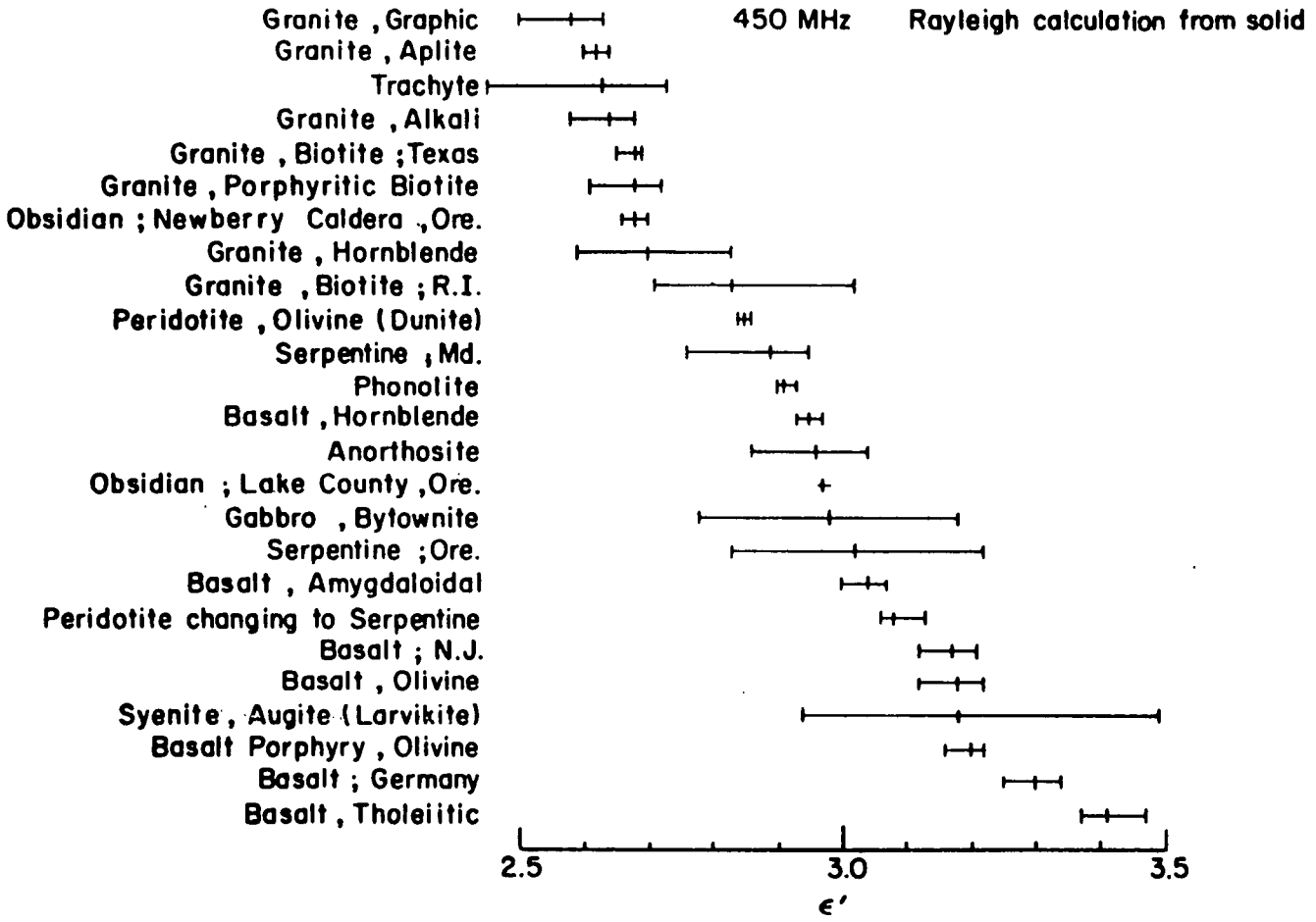

Figure 26. The permittivities of powdered rocks at 40% porosity. From Campbell and Ulrichs (1969)).

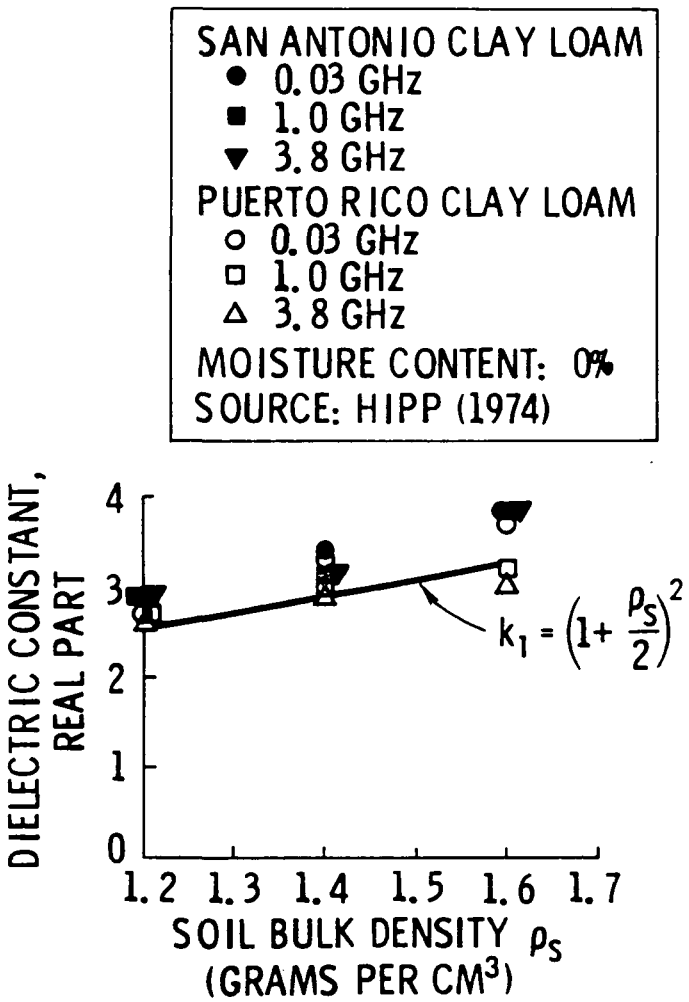

Figure 27. Effect of bulk density on the relative dielectric constant.

Bulk density has an important indirect effect on the relationship between dielectric constant and soil moisture content. Figure 28 presents some data for Openwood Street silt (Lundien, 1971); it is apparent that the k_1 values measured for this soil can be represented adequately by a single curve regardless of the degree of compaction if expressed on the volume basis. When moisture contents are calculated on the weight basis, then according to Eqs. (8) and (9), individual data points should shift to the left (usually, $\rho_s > 1.0$ g/cm^3). This is demonstrated in Figure 28 for bulk densities of 1.2 and 1.6 g/cm^3. As a result of the shift an artificial uncertainty is introduced into the k_1 versus moisture relationship. For example, k_1 lies between approximately 12.0 and 14.0 for moisture content of 0.25 g/cm^3 when the scatter around the mean curve is taken into account. It contrast, k_1 varies between 14.0 and 21.5 for a moisture content of 25% if bulk density of the measured sample ranges from 1.2 to 1.6 g/cm^3.

The above uncertainty is included in data presented in Figures 2 through 15. It cannot be removed unless bulk density values are also given. The intensity of compaction added in some cases (e.g., Wiebe, 1971) is not sufficient because for a constant compaction value, bulk density varies as a function of soil type and moisture content; this is indicated in Figure 29 which was prepared from data by Lundien (1971). Unfortunately, a large proportion of soil dielectric constant measurements available lacks the bulk density information. The artificial uncertainty is introduced in a similar manner into the k_2 versus moisture relationship.

3.3 Soil Type

The term soil type was previously used in soil survey to designate a subdivision of soil series based on the particle size distribution of the surface soil (Soil Survey Staff, 1951). In the Comprehensive Soil Classification System employed by the U.S.D.A. since 1965, the designation soil type has been replaced by soil phase (Soil Survey Staff, 1960). The term soil type is still being used in the remote sensing literature. It should be noted that the textural classes on the basis of which soil types have been defined have not changed (Figure 30).

Results of various experiments indicate that at higher frequencies, the dielectric constant is almost unaffected by the chemical and mineralogical composition of rocks (Campbell and Ulrichs, 1969) or soils (Lundien, 1971) except where significant amounts of metallic or magnetic minerals are present (Edgerton et al., 1971). Differences among soil types observed at these frequencies (Lundien 1966, 1971; Wiebe, 1971) have been attributed to soil water interactions which depend on the particle size distribution.

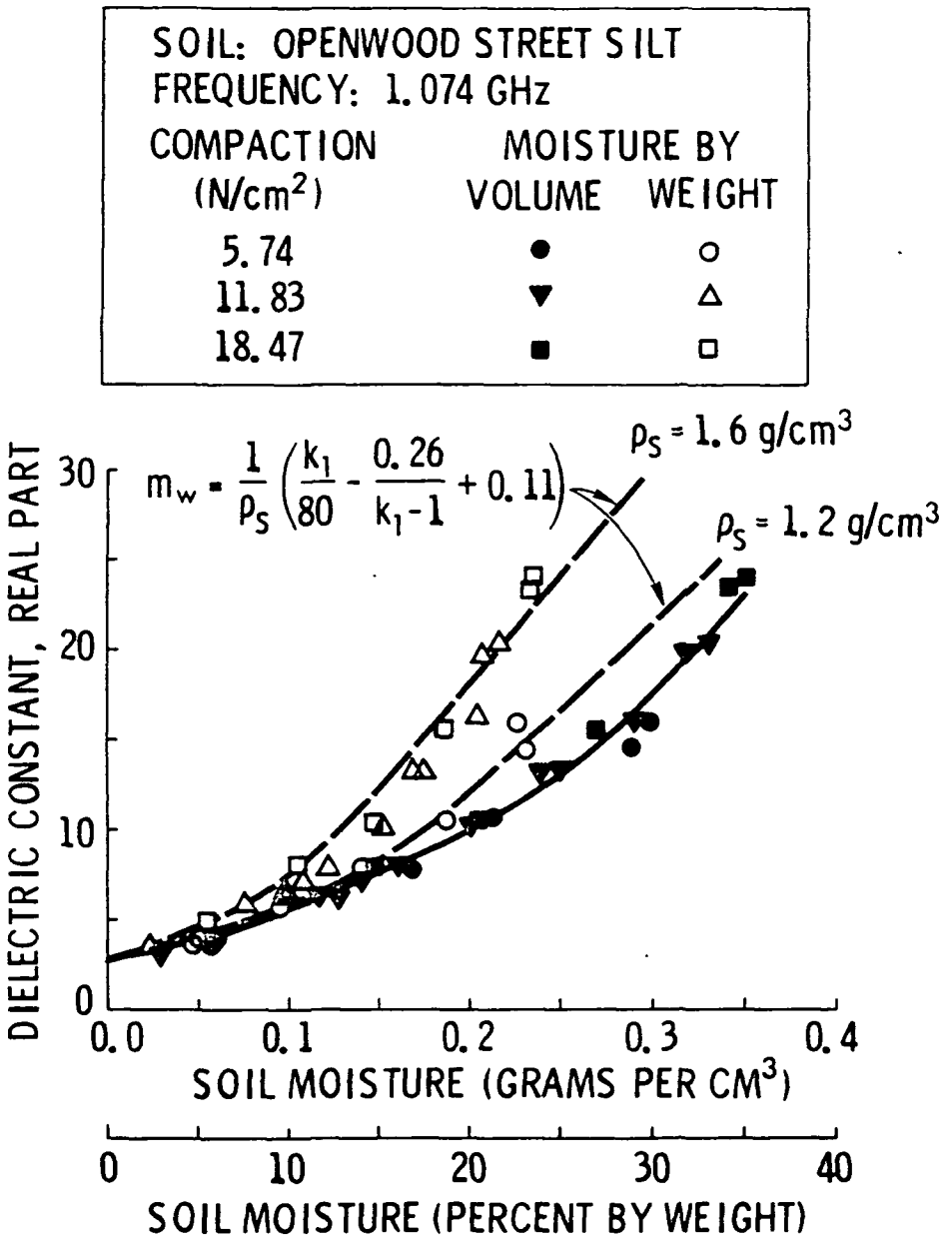

Figure 28. Change in relative dielectric constant due to soil moisture units used.

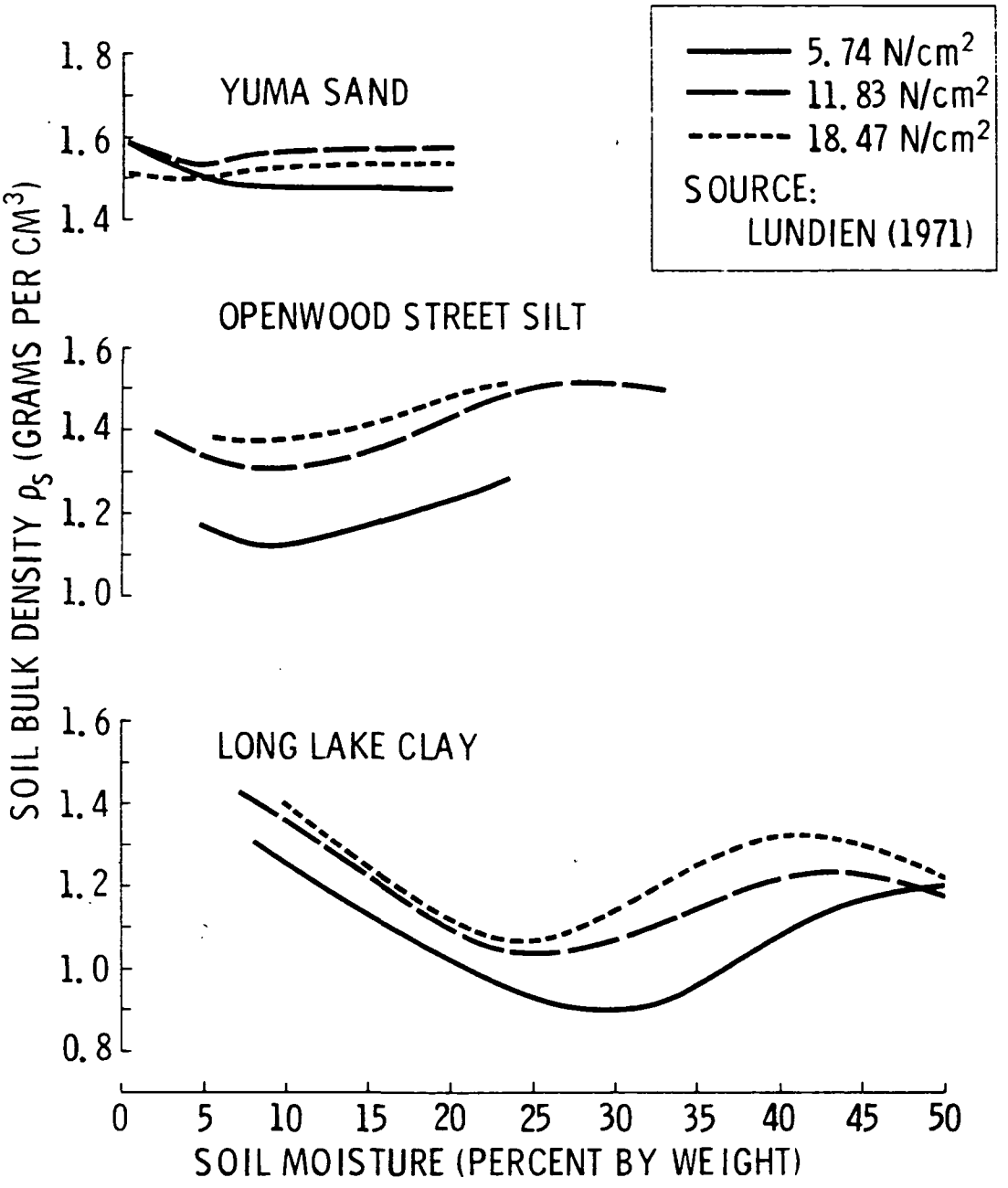

Figure 29. Bulk density variation due to compaction as a function of gravimetric water content.

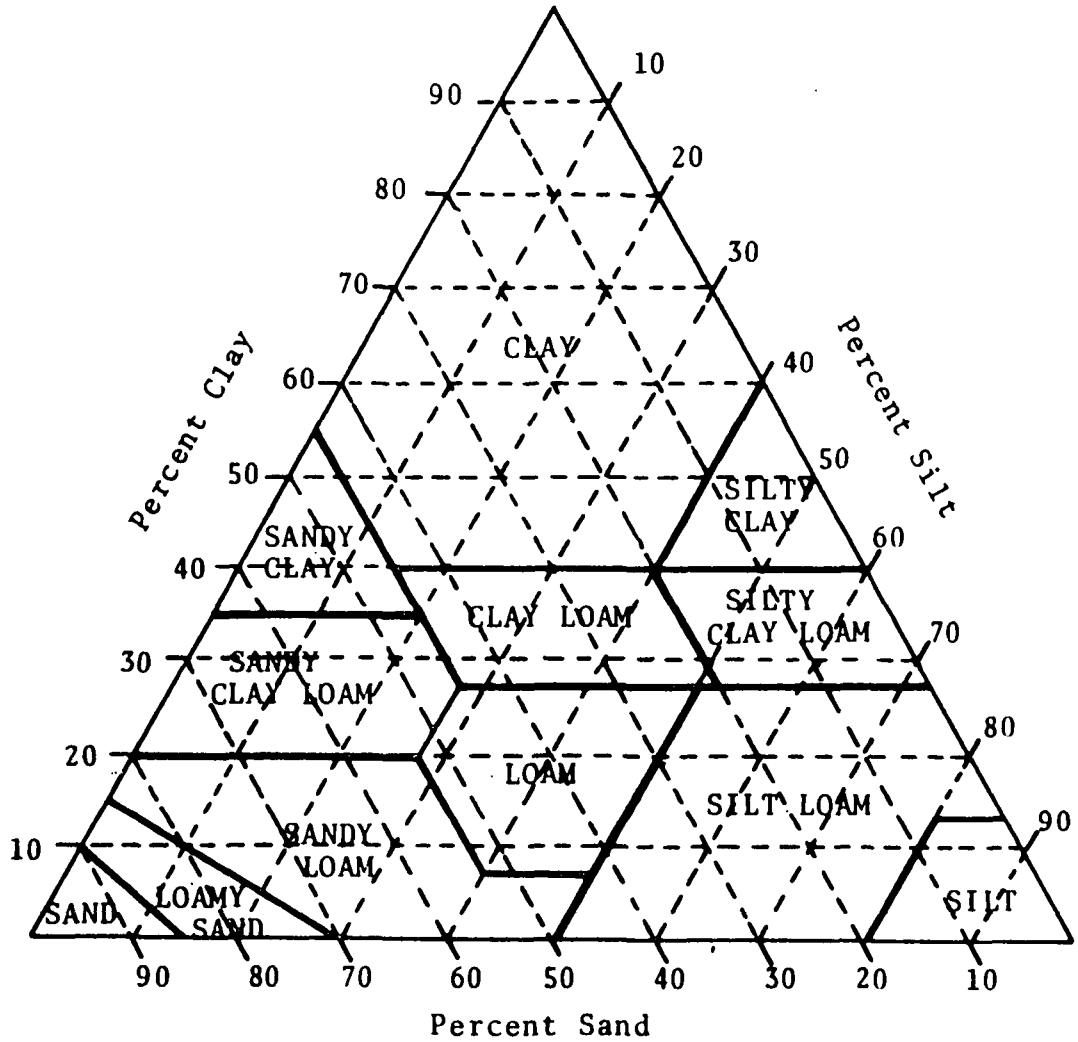

Figure 30. Soil textural triangle.

In some studies (e.g., Hoekstra and Delaney, 1974), differences between dielectric properties of various soil types have not been observed. This topic was discussed in some detail in Section 3.1.

At low frequencies, soil type modifies the dielectric properties by its ionic complex characteristics. In particular, the dielectric loss increases with increasing proportion of clay particles in the soil, due to presence of larger amounts of ions at the exchange sites. From the measurements available, this effect appears to become important below 0.3 GHz.

3.4 Temperature

The dielectric constant of solid soil particles is relatively independent of temperature. For example, Compbell and Ulrichs (1969) found small differences at 35 GHz (<1.0) between real parts of the dielectric constant of five rocks (tholeiitic basalt, olivine basalt, quartz, aplite granite, dunite) measured at various temperatures (Figure 31). On the other hand, dielectric constant of water may be calculated accurately as a function of temperature (Paris, 1969). Lundien (1971) developed such an expression based on experimental data measured at L-band using both distilled and tap water:

$$k_1 = 88.6 - 0.368\ T$$

where T is temperature in ^{o}C.

Since soil almost always contains some water (unless oven-dried), its dielectric constant depends on temperature. This has been confirmed experimentally by Poe *et al.* (1971) who observed that the real part of the dielectric constant of dry soil exhibited no change when temperature was raised from 20°C to 60°C but such change occurred when a small amount of water was present.

3.5 Frequency

Data presented in Figures 2 to 15 indicate little difference between the dielectric constant values of dry soils at frequencies between 0.13 GHz and 37 GHz. Lundien's (1971) measurements at five frequencies between 0.01 GHz and 1.499 GHz showed that the dielectric constant was approximately constant for all soils and frequencies above 1.0 GHz; the values increased below approximately 0.05 GHz, 0.15 GHz and 0.45 GHz for sand, silt, and clay, respectively.

These data are in agreement with the results measured for rocks: Campbell and Ulrichs (1969) found that the dielectric constant values of a variety of terrestrial rocks and minerals exhibited only small differences between two frequencies, 450 MHz and 35 GHz; materials that displayed differences tended to be the inhomogeneous ones (Figure 32).

It should be noted again that the above results hold for dry materials; the dielectric constant becomes frequency dependent when water is added. Hoekstra and Delaney (1974) presented k_1, k_2, and loss tangent (k_2 / k_1) values for a silty clay at 15% moisture content (Figure 33). Values above 0.1 GHz represent Suffield silty clay (Figures 17 through 24) while data at lower frequencies were obtained from a study by Smith-Rose (1933). The dielectric loss can be seen to be small around 0.1 GHz but increases in both directions. At higher frequencies, the presence of water causes increase in dielectric loss. The shape of the curves at lower frequencies will depend on soil type.

4.0 REPRESENTATIVE DIELECTRIC VALUES

As evident from the previous section, a large number of dielectric constant measurements by various investigators have been made. The data exhibit a scatter which is due to both inherent soil variability and experimental error. To use these measurements for analyzing microwave signal variations with moisture content, however, only one representative data set is needed. Results of section 3.0 suggest that the dielectric constant vs. soil moisture relationship should be given (i) in terms of volumetric water content, and (ii) for various frequency/soil type combinations; lower frequencies are more relevant because of the higher penetration depth.

Using data shown in Figures 17 through 24, average curves were drawn through the points for both k_1 and k_2 for three frequencies (1.3 GHz, 4.0 GHz and 10.0 GHz) and three soil types (sand, loam, and clay). Values read off from the average curves (Figures 34-36) are given in Table 1. The last column of Table 1 gives the primary data source for the average curves; it shows that the three frequencies and soil types represent a mean condition only.

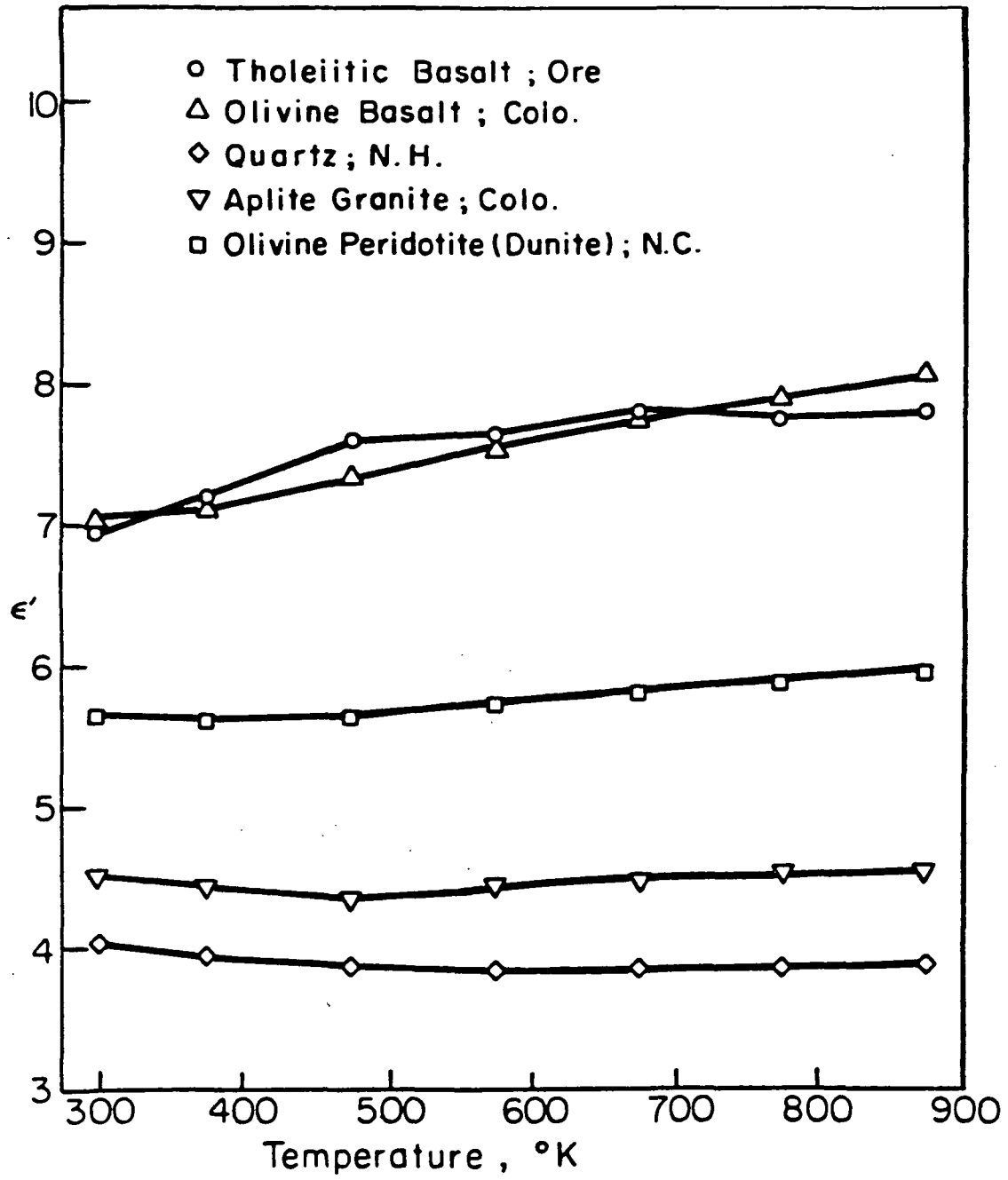

Figure 31. The Permittivity of rocks at 35 GHz as a function of temperature (From Campbell and Ulrichs (1969)).

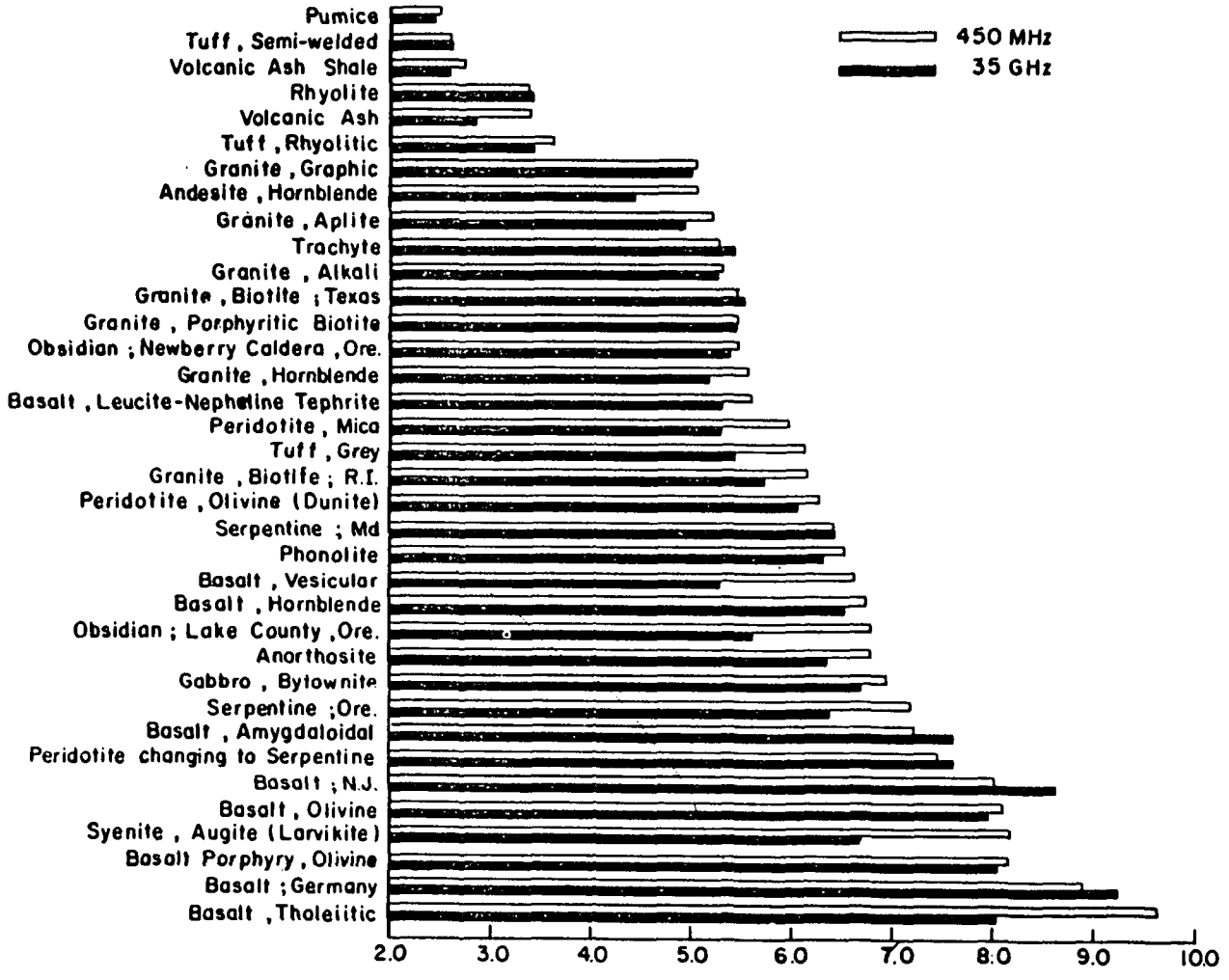

Figure 32. A comparison of the permittivities of solid rocks at 450 MHz and 35 GHz. (From Campbell and Ulrichs (1969)).

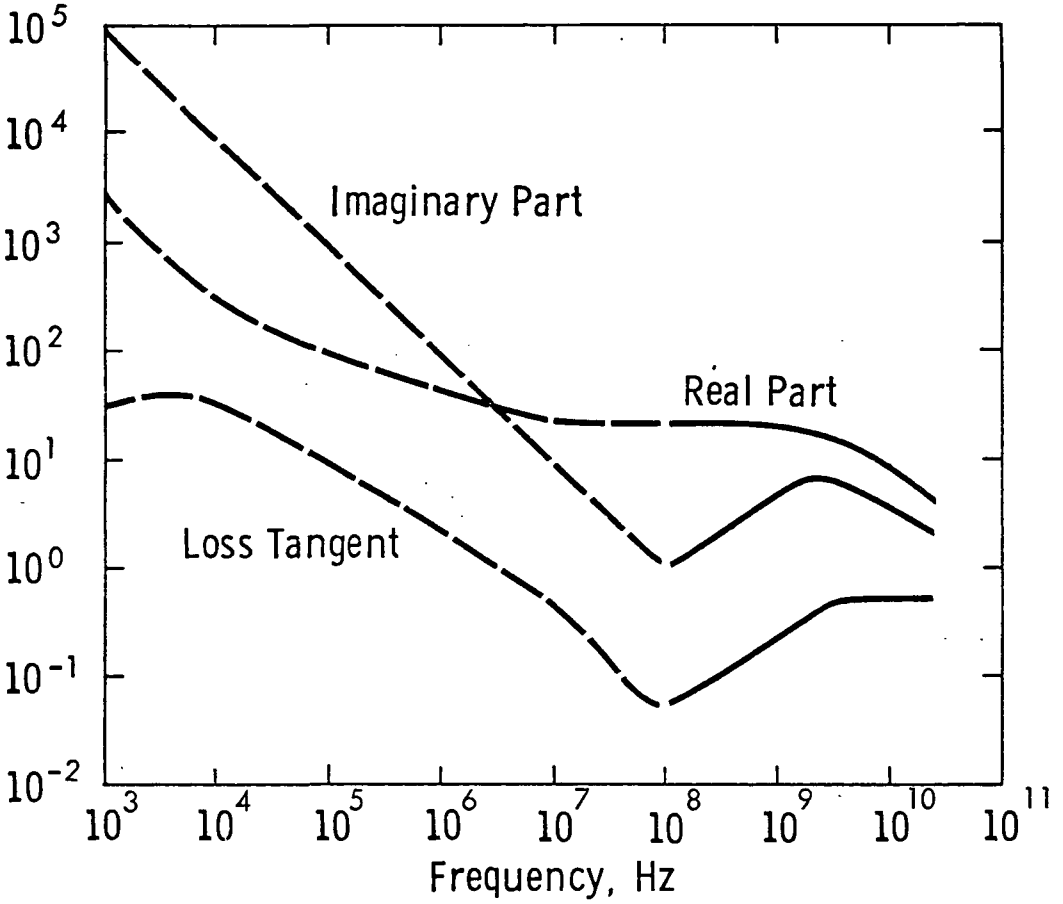

Figure 33. Real and imaginary part of the relative dielectric constant as a function of frequency for a silty clay, moisture content 15% by weight. (From Hoekstra and Delaney (1974)).

Table 1. Representative Relative Dielectric Constant Values for Three Frequencies and Three Soil Types.

Frequency GHz	Soil Type	Soil Moisture g/cm^3	Real Part k_1	Imaginary Part k_2	Primary Data Base (soil, frequency, source)
1.3	Sand	0.00	3.4	0.0	Yuma sand; 1.1, 1.5; Lundien (1971)
		0.05	4.5	0.1	
		0.10	6.2	0.3	
		0.15	8.8	0.6	
		0.20	12.0	0.7	
		0.25	15.6	1.0	
		0.30	19.1	1.3	
	Loam	0.00	3.4	0.0	Openwood Street silt; 1.1, 1.5; Lundien (1971)
		0.05	4.5	0.3	San Antonio clay loam; 1.0; Hipp (1974)
		0.10	6.0	0.6	Puerto Rico clay loam; 1.0; Hipp (1974)
		0.15	7.6	0.9	
		0.20	9.8	1.2	
		0.25	12.6	1.5	
		0.30	16.5	1.8	
		0.35	20.5	2.3	
		0.40	24.5	2.9	
	Clay	0.00	3.0	0.0	San Antonio clay loam; 1.0; Hipp (1974)
		0.05	4.0	0.5	Puerto Rico clay loam; 1.0; Hipp (1974)
		0.10	5.2	1.0	Long Lake clay; 1.1, 1.5; Lundien (1974)
		0.15	6.7	1.4	
		0.20	8.2	1.9	
		0.25	10.4	2.4	
		0.30	13.5	2.9	
		0.35	17.4	3.6	
		0.40	21.2	4.5	
		0.45	25.3	5.7	
4.0	Sand	0.00	3.0	0.1	Manchester fine sand; 4.0; Hoekstra and Delaney (1974)
		0.05	3.9	0.6	
		0.10	5.3	1.1	
		0.15	7.2	1.7	
		0.20	9.9	2.3	
		0.25	13.2	3.0	
		0.30	16.9	3.8	

(Continued) Table 1. Representative Relative Dielectric Constant Values for Three Frequencies and Three Soil Types.

Frequency GHz	Soil Type	Soil Moisture g/cm^3	Real Part k_1	Imaginary Part k_2	Primary Data Base (soil, frequency, source)
	Loam	0.00	3.0	0.1	Fairbank silt; 4.0; Hoekstra and Delaney (1974)
		0.05	3.8	0.5	San Antonio clay loam; 3.8; Hipp (1974)
		0.10	4.8	0.9	Puerto Rico clay loam; 3.8; Hipp (1974)
		0.15	6.3	1.4	
		0.20	8.5	2.0	
		0.25	11.6	2.5	
		0.30	15.4	3.2	
		0.35	19.2	3.8	
		0.40	23.0	4.4	
4.0	Clay	0.00	3.8	0.1	Goodrich clay; 4.0; Hoekstra and Delaney (1974)
		0.05	4.6	0.5	Suffield silty clay; 4.0; Hoekstra and Delaney (1974)
		0.10	5.6	1.0	Puerto Rico clay loam; 3.8; Hipp (1974)
		0.15	6.8	1.5	San Antonio clay loam; 3.8; Hipp (1974)
		0.20	9.1	2.2	
		0.25	12.3	2.8	
		0.30	16.1	3.5	
		0.35	19.9	4.3	
		0.40	23.7	5.1	
		0.45	27.5	5.9	
10.0	Sand	0.00	2.4	0.1	Manchester fine sand; 10.0; Hoekstra and Delaney (1974)
		0.05	3.6	0.7	
		0.10	5.1	1.4	
		0.15	7.0	2.3	
		0.20	8.9	3.3	
		0.25	11.0	4.5	
		0.30	13.1	5.8	
	Loam	0.00	2.4	0.2	Fairbanks silt; 10.0; Hoekstra and Delaney (1974)
		0.05	3.4	0.6	
		0.10	4.7	1.1	
		0.15	6.4	1.8	
		0.20	8.3	2.8	
		0.25	10.2	3.9	
		0.30	12.2	5.0	
		0.35	14.2	6.1	
		0.40	16.2	7.2	

(Continued) Table 1. Representative Relative Dielectric Constant Values for Three Frequencies and Three Soil Types.

Frequency GHz	Soil Type	Soil Moisture g/cm^3	Real Part k_1	Imaginary Part k_2	Primary Data Base (soil, frequency, source)
	Clay	0.00	3.6	0.2	Clay; 10.0; Matzler (1970)
		0.05	3.8	0.6	Goodrich clay; 10.0; Hoekstra and Delaney (1974)
		0.10	4.6	1.1	Suffield silty clay; 10.0; Hoekstra and Delaney (1974)
		0.15	6.0	1.9	
		0.20	8.2	3.0	
		0.25	10.4	4.2	
		0.30	12.6	5.4	
		0.35	14.8	6.7	
		0.40	17.0	8.0	
		0.45	19.2	9.3	

Since the representative dielectric constant curves shown in Figure 34-36 were related to volumetric moisture, the large number of measurements shown in Figure 2 through 15 could not be used. It was of interest to determine, however, whether the two types of dielectric values are similar for equivalent conditions. To this end, average k_1 and k_2 values were extracted from Figures 2 through 15 for two frequencies (1.3 GHz and 10.0 GHz) and three soil types (sand, loam, and clay). The average curves were based primarily on the data by Leschanskii, et al. (1971), Lundien (1971), Wiebe (1971) and Matzler (1970). Secondly, skin depth was computed as a function of moisture for every frequency/soil type combination; skin depth was used for the comparison because it reflects the effect of both k_1 and k_2. A comparison of the "volumetric" skin depth values to the "gravimetric" skin depths showed, with one exception, a very good correspondence if the gravimetric moistures were multiplied by bulk density values between 1.4 and 1.6 g/cm^3. The one exception was loam at 1.3 GHz which was located about half distance between sand and clay based on the "volumetric" skin depth (Figure 37) but was very close to clay if the skin depths are computed from the "gravimetric" data set. An inspection of the original data showed that this discrepancy was due to relatively high k_2 values for loam given by Leschanskii et al. (1971, see Figure 5) which resulted in a higher attenuation (Eq. 4) and therefore smaller skin depth. Since physical properties of a loamy soil are between those of sand and clay, it was decided that the "volumetric" data set for loam at 1.3 GHz was adequate. The good correspondence between skin depth values for "gravimetric" and "volumetric" data sets indicates that the values given in Table 1 and Figures 34-36 are representative of the available measurements at the three frequencies.

Figure 37 shows skin depth as a function of moisture content, computed from values in Table 1 for a homogeneous uniformly moist soil. The skin depth values decrease rapidly at low moisture contents and more slowly as the moisture content increases. There is almost an order-of-magnitude difference between the three frequencies. To obtain some information about subsurface moisture contents, low frequencies are clearly necessary. The magnitude of a remotely measured microwave signal is related to the reflection coefficient (for active sensors) or emissivity (for passive sensors) of the soil. Power reflection coefficient (Eq. 1,2) and emissivity (Eq. 3) were calculated for normal incidence from data in Table 1. The results (Figure 38) show a small variability due to soil type or frequency for the cases considered; at any moisture content, the range was less than 0.07. The reflection

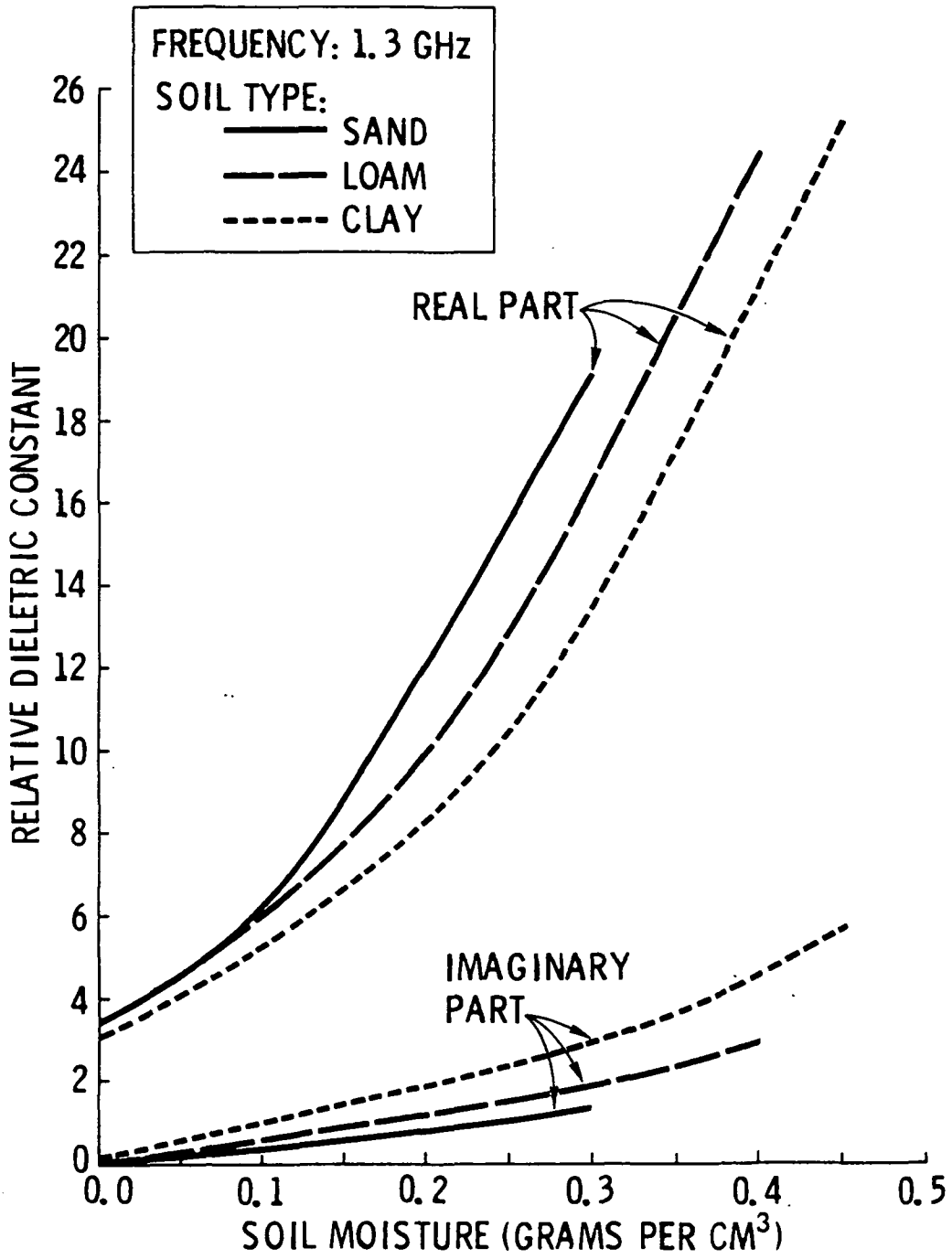

Figure 34. Representative dielectric constant values as a function of volumetric water content for sand, loam, and clay at 1.3 GHz.

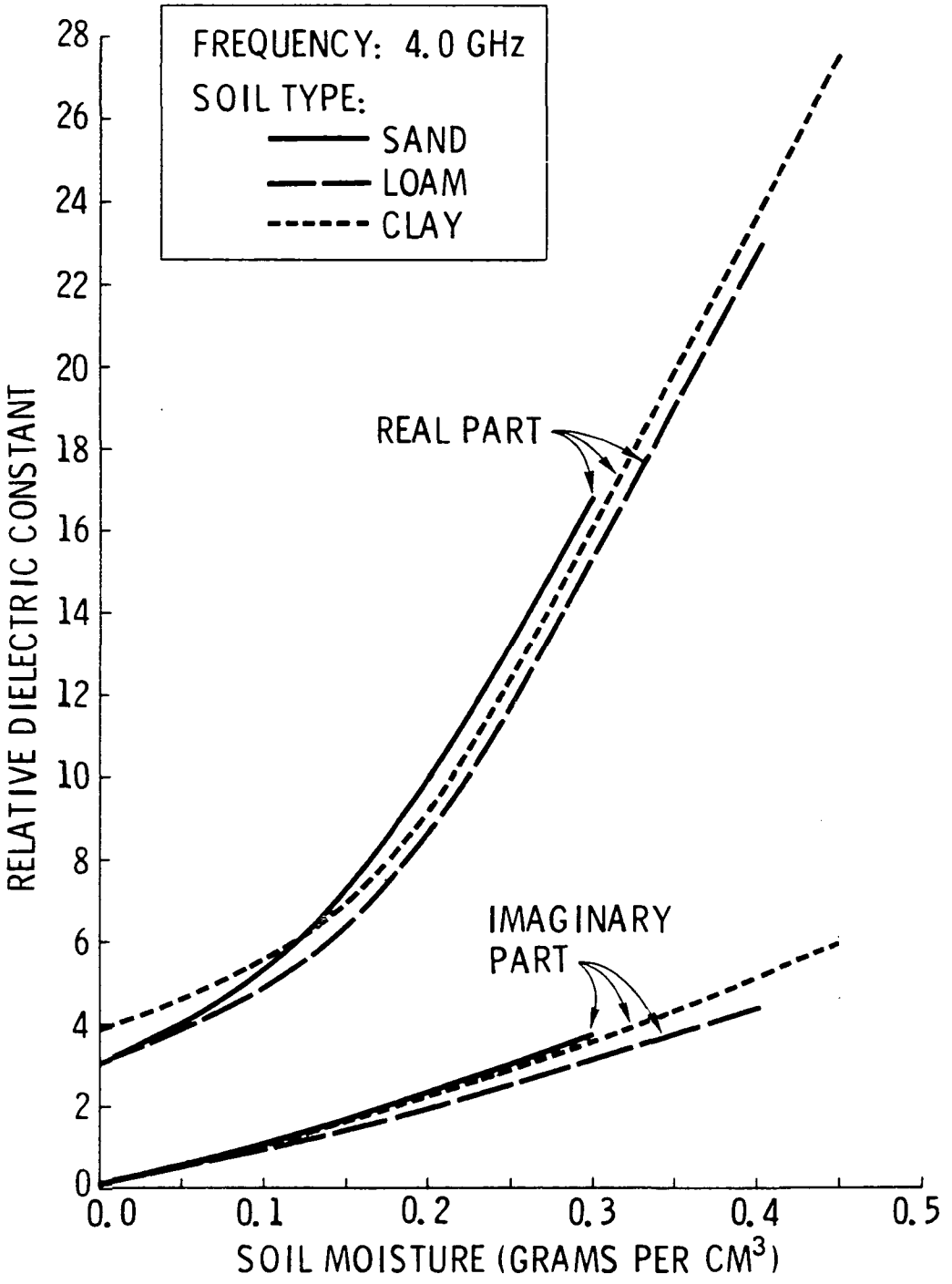

Figure 35. Representative dielectric constant values as a function of volumetric water content for sand, loam, and clay at 4.0 GHz.

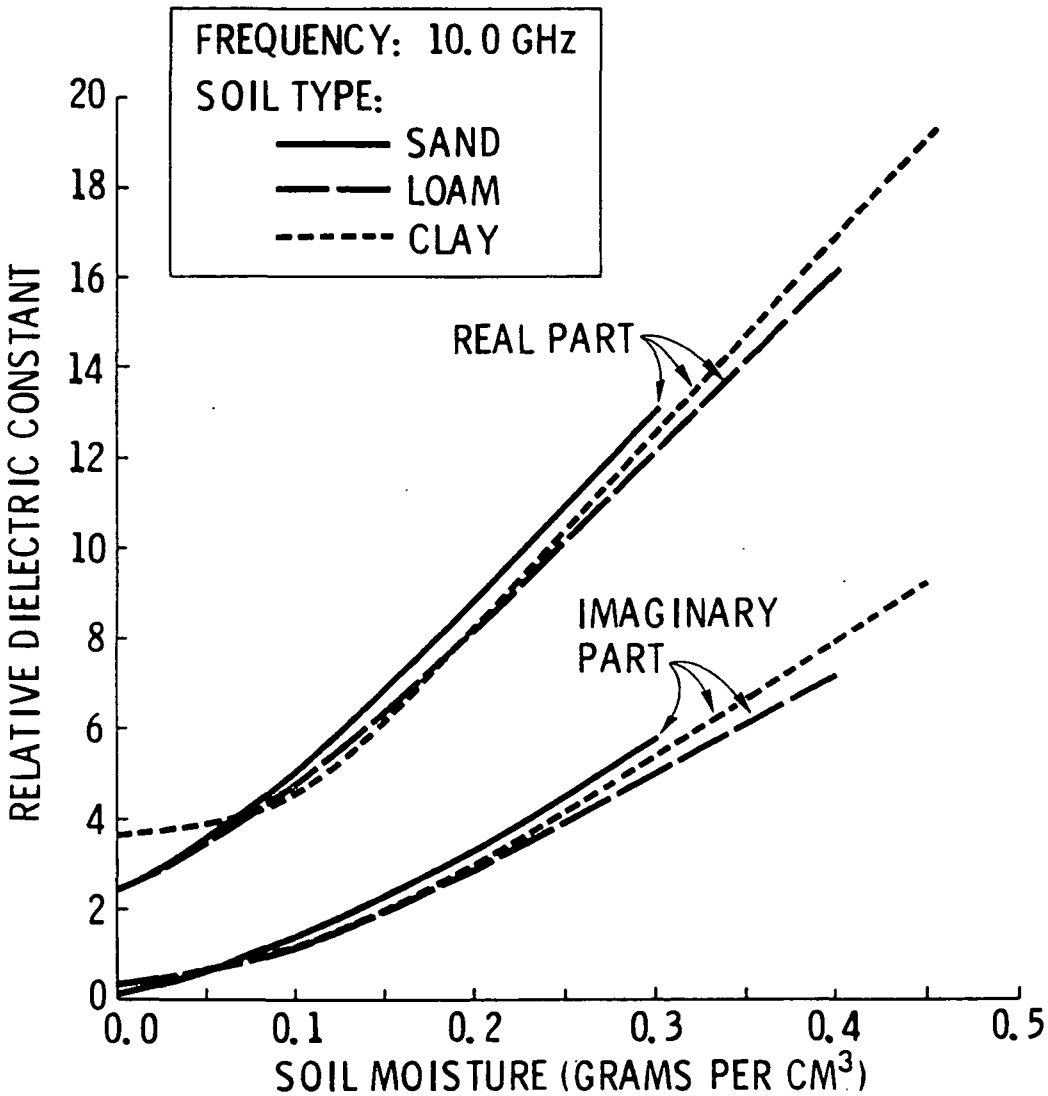

Figure 36. Representative dielectric constant values as a function of volumetric water content for sand, loam, and clay at 10.0 GHz.

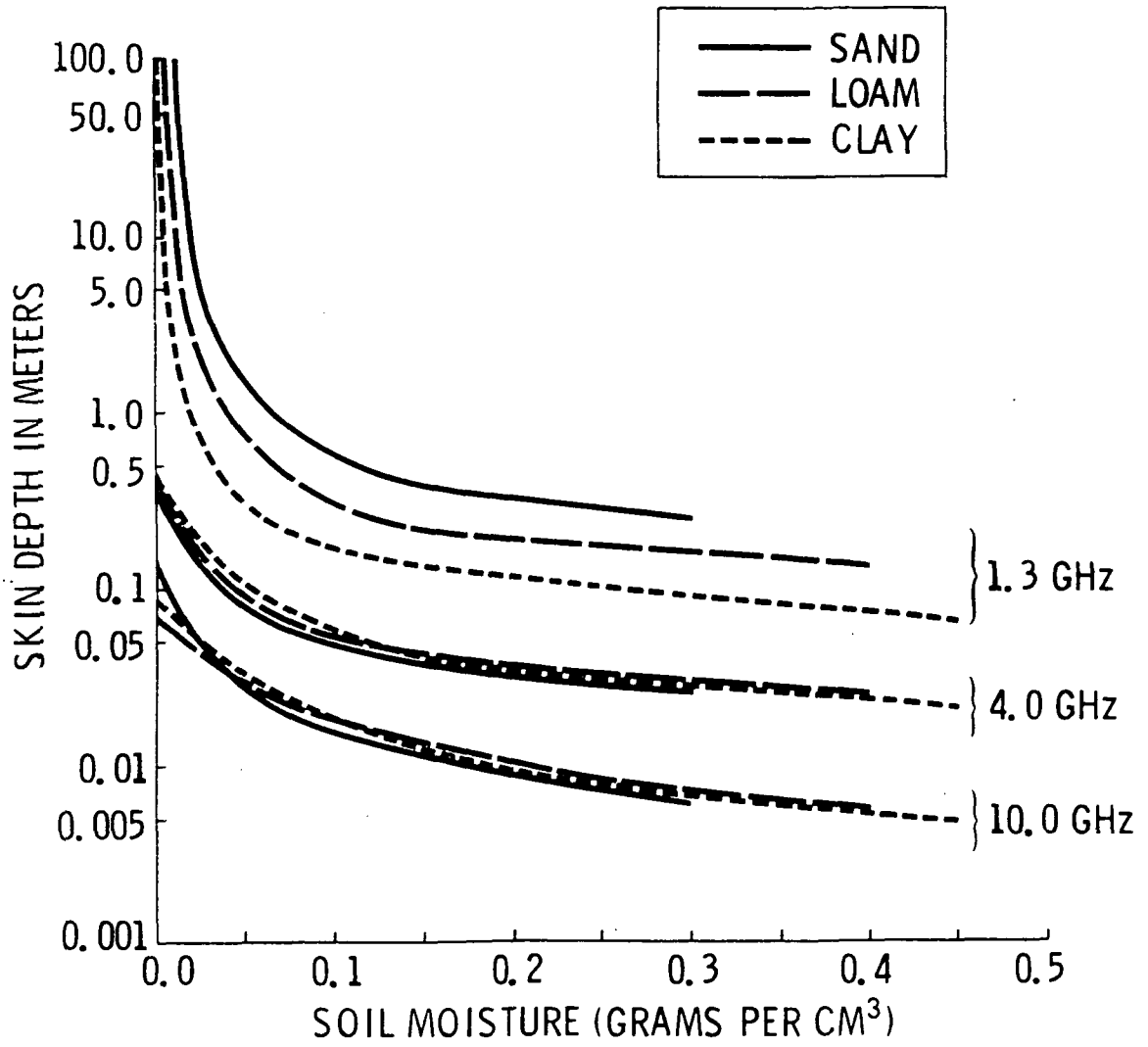

Figure 37. Skin depth as a function of volumetric water content, frequency, and soil type.

coefficient changed from 0.08 (-11.0 dB) for a dry soil to 0.45 (-3.5 dB) at 0.45 g/cm^3, an average increase of .0082 for every 0.01 g/cm^3. Emissivity changed in the opposite direction (Eq. 3). Figure 38 thus suggests that the proportion of microwave energy normally incident on a smooth, homogeneous uniformly moist soil which is reflected from the soil is practically independent of frequency and soil type.

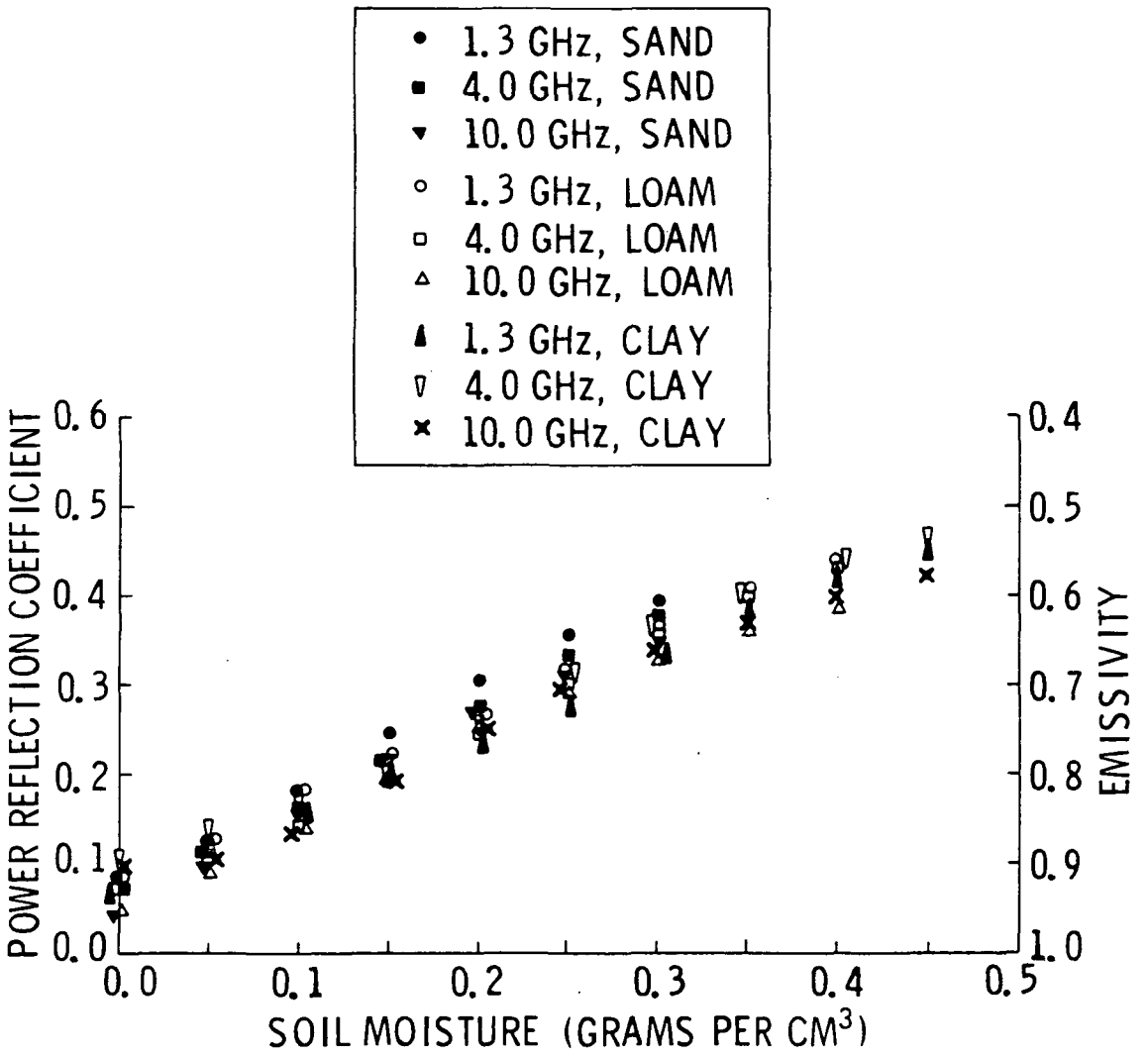

Figure 38. Power reflection coefficient and emissivity as a function of volumetric water content, frequency, and soil type.

APPENDIX A.

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